Finding and Measuring Sub-Surface Water on Mars and the Moon with neutron and gamma-rays

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Abstract

There are several complementary methods for the detection of water on planetary bodies such as the Moon and Mars. Sub-surface water down to ~ 1 meter can be detected the presence of hydrogen by nuclear methods. The hydrogen, if present, has a significant moderating (slowing) effect on fast neutrons. The ~MeV neutrons are produced naturally by cosmic-rays, or they can be artificially produced by a pulsed neutron source carried on a planetary rover, as will be described. The presence of hydrogen, which is presumed to be due to water, can also be determined by observations of the unique gamma-ray signature produced as slow neutrons are captured by hydrogen to produce deuterium.

The LEND instrument on the Mars Odyssey spacecraft made pioneering observations of sub-surface water on Mars with its neutron observations. These results will be described some detail, including the most recent analysis of sub-surface water mapping and temporal changes in its distribution.

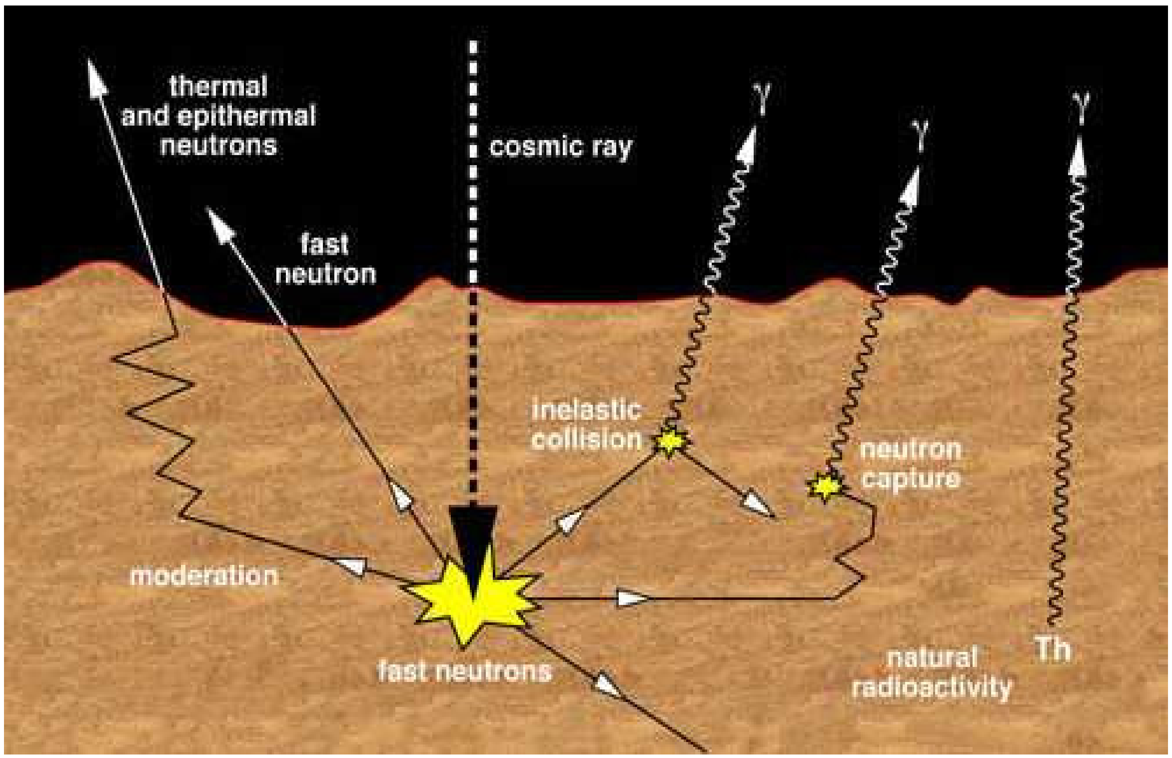
2008

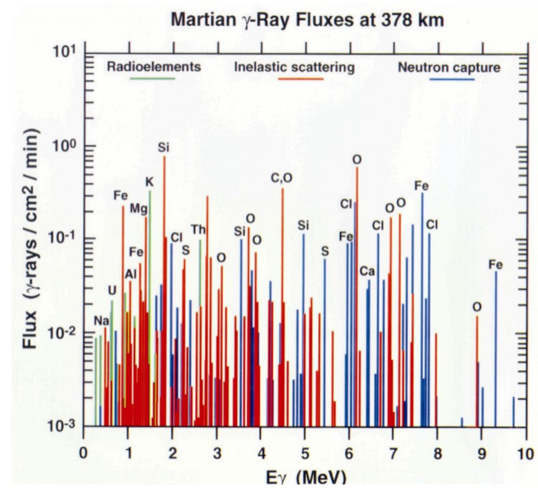
Our group at IKI is also quite busy with the development of the neutron instrument, LEND, for the Lunar Reconnaissance Orbiter (LRO), scheduled to be launched in ~~1998~~. This instrument is more sensitive and more directional that the Mars HEND instrument that was flown on Mars Odyssey 2001. Its design and capabilities will be described, along with plans for future larger, orbiters and rovers in this field.

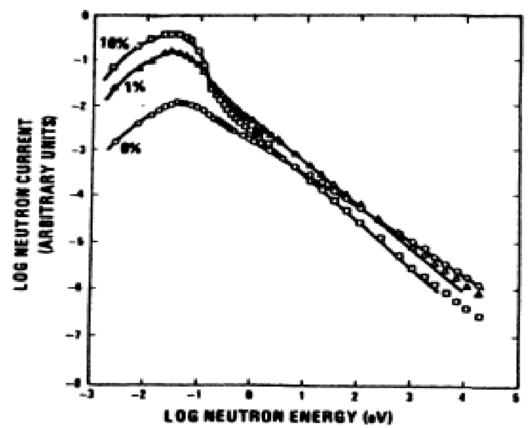
Cooperation in Russia	Cooperation in US
Institute for Space Research	University of Alabama
Sternberg Astronomical Institute	NASA Jet Propulsion Laboratory
Joint Institute for Nuclear Research	NASA Goddard Space Flight Center
All-Russia Institute for Automatics	University of Maryland
Institute for Physics of Nuclear reactors	Catholic University
Institute for Mechanical Engineering	Computer Space Science Corporation
A.F.Ioffe Physical-Technical Institute	

Russian instruments for NASA missions are based on using the best technology achievements of Federal Space Agency and Federal Agency of Atomic Energy of Russian Federation

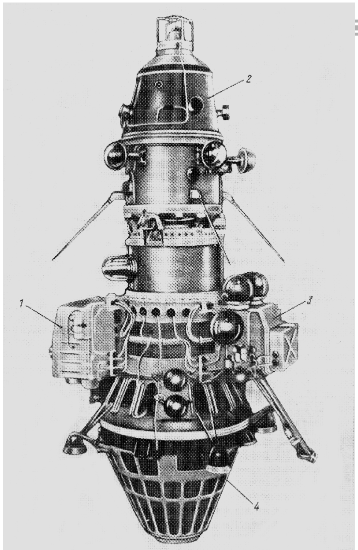
Nuclear emission from surface of Moon, Mars and no-atmosphere celestial bodies is produced by Galactic Cosmic Rays or by artificial sources of energetic neutrons

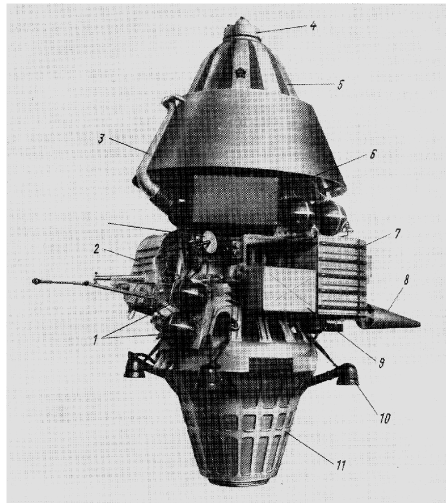






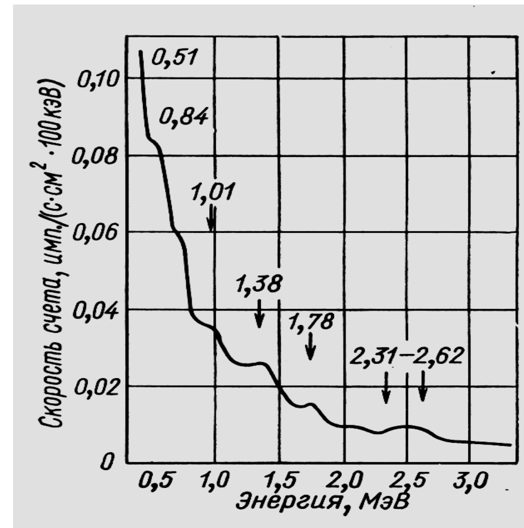
NSSTC – Special Seminar

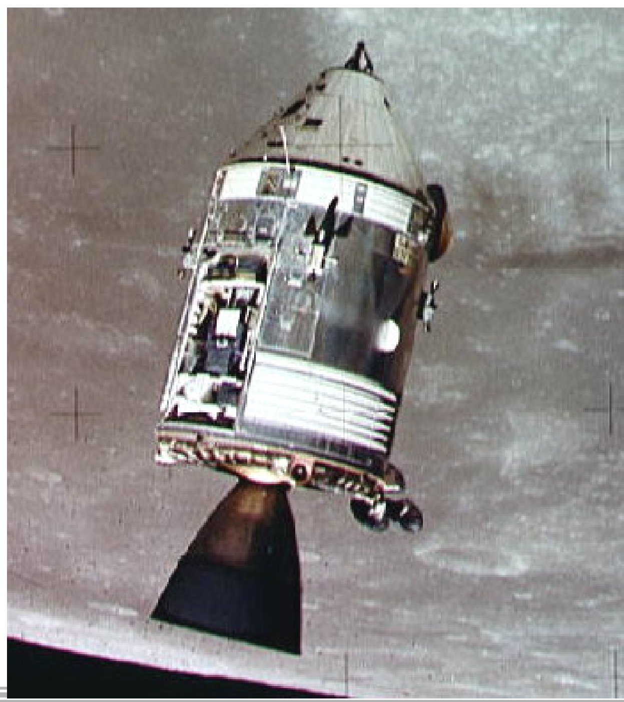




Luna 10, April 1966

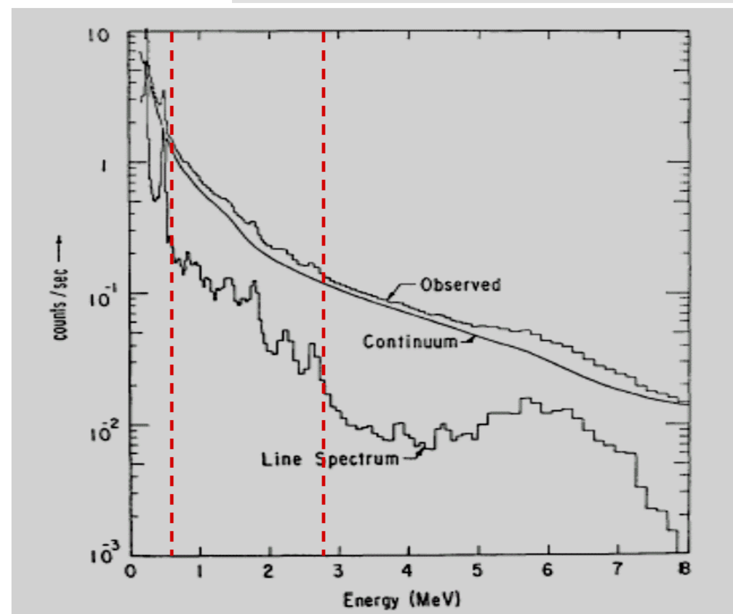
Luna 12 October 1966

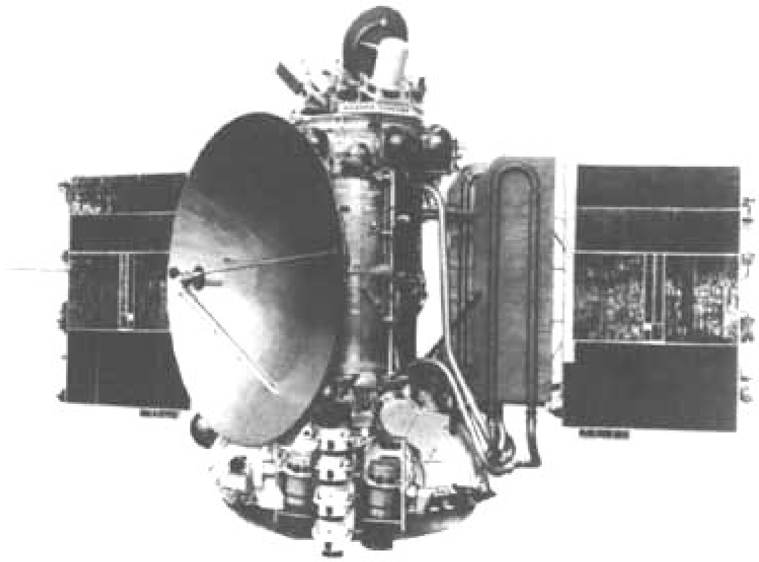




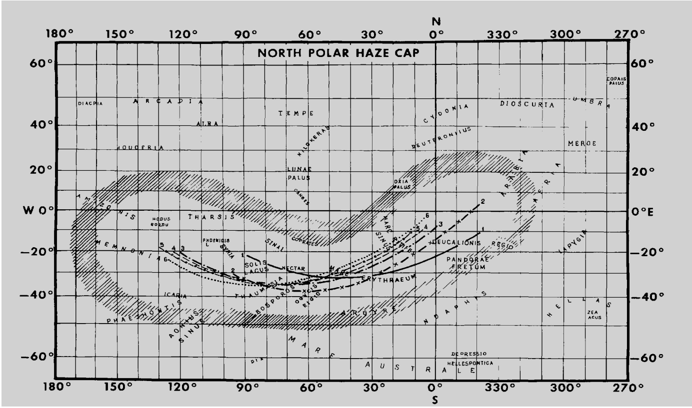
Apollo 15, July 1971

Apollo 16 April 1972

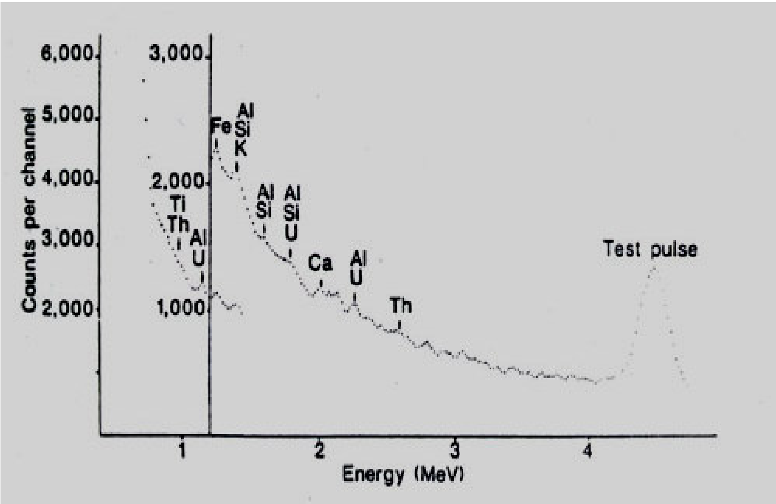


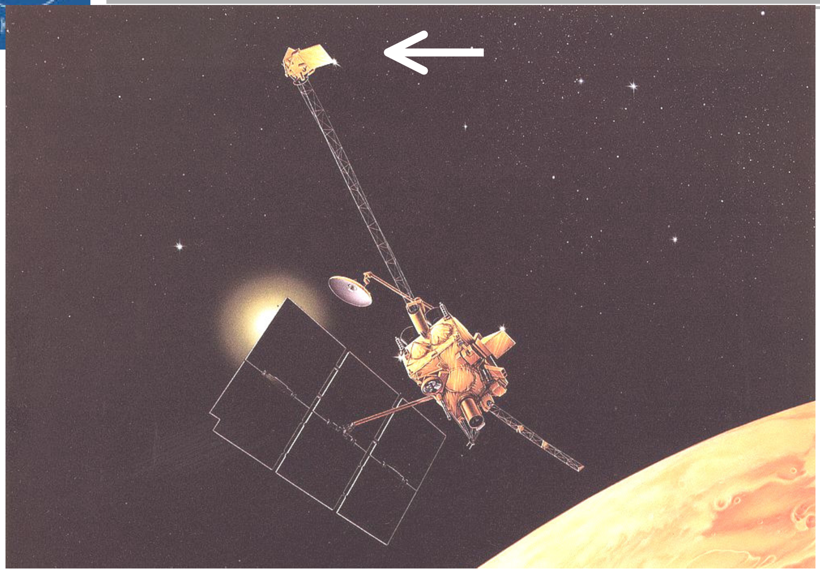


First gamma-rays from Mars – July 1971, “Mars-5”

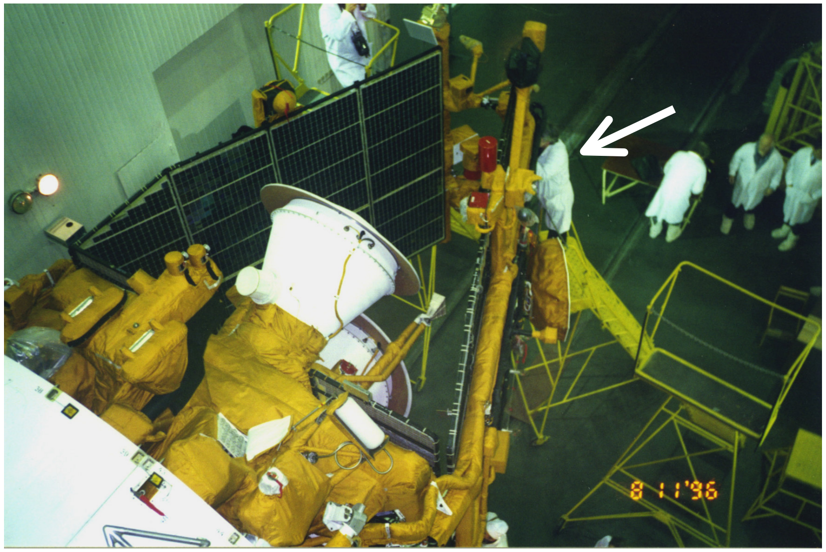


«Phobos-2», February 1989





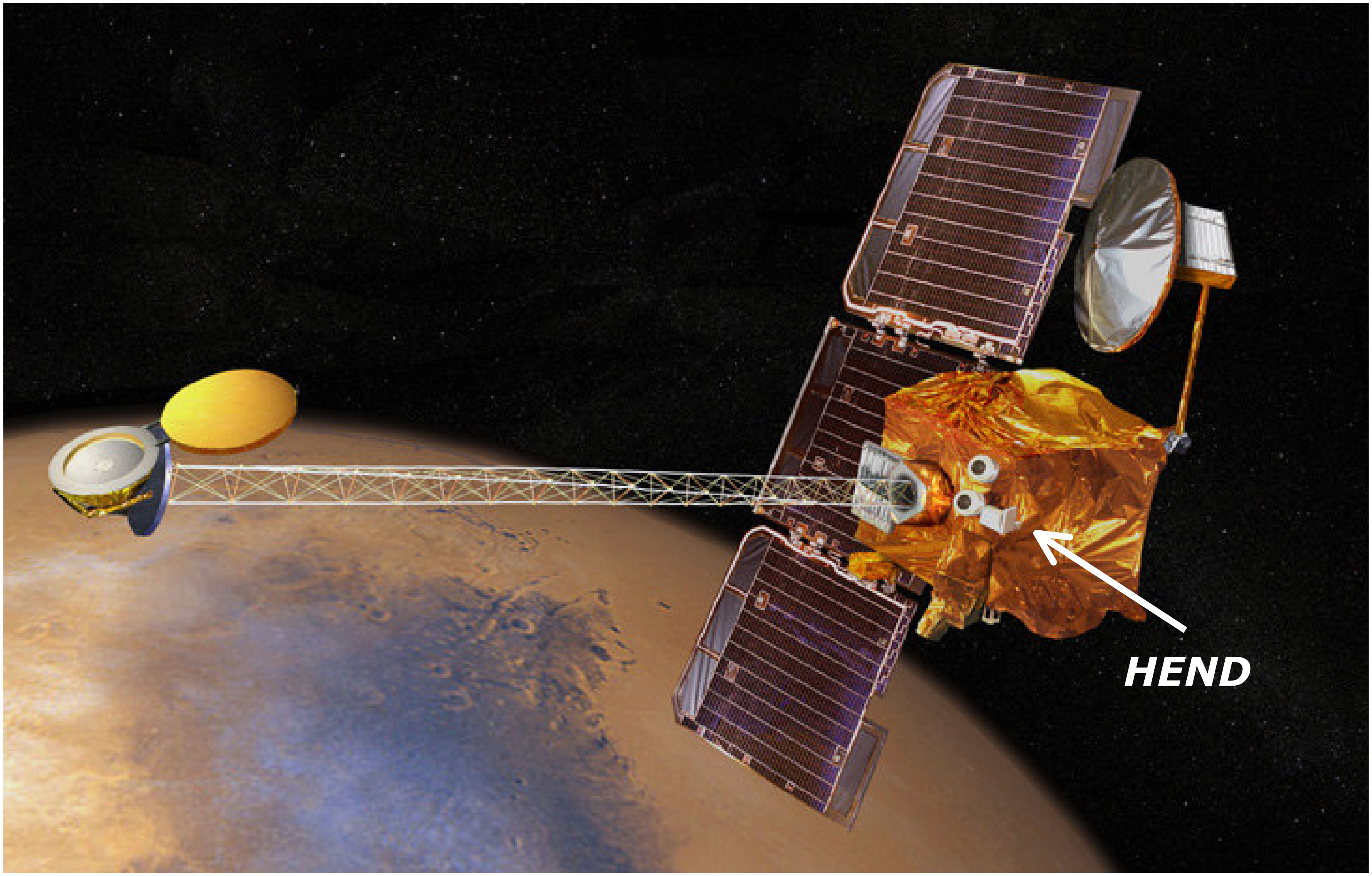
NASA “Mars Observer”, September 1992

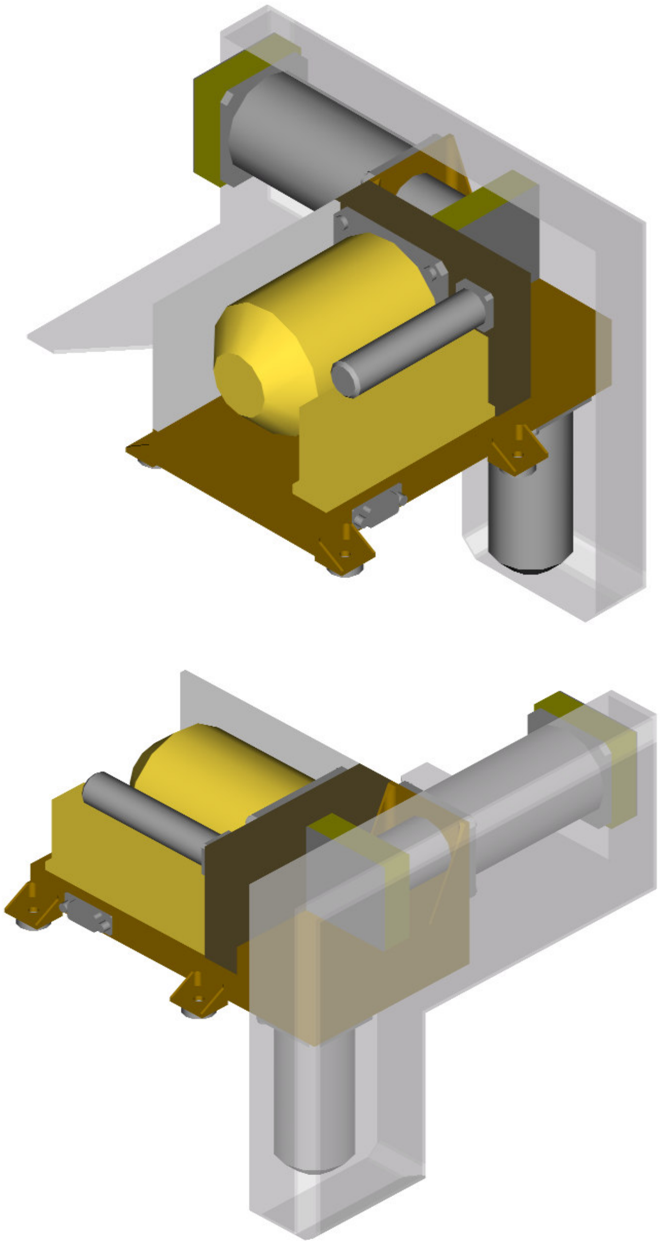


Russian “Mars-96”, November 1996

Russian High Energy Neutron Detector (HEND) on NASA "2001 Mars Odyssey"

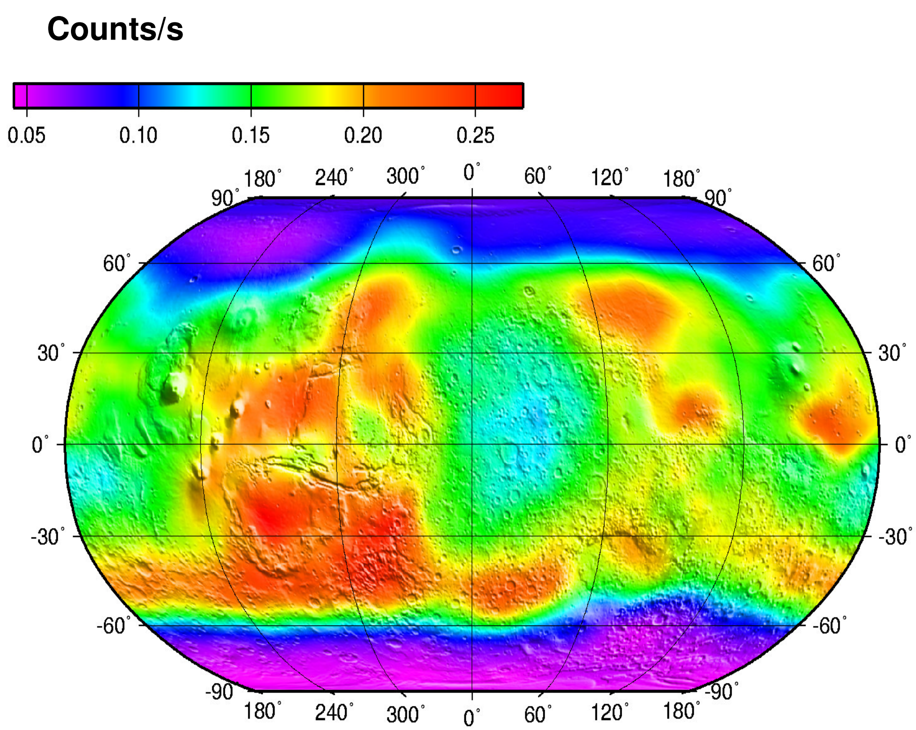
NASA "2001 Mars Odyssey", Gamma-Ray Spectrometer suite, April 2001 - now

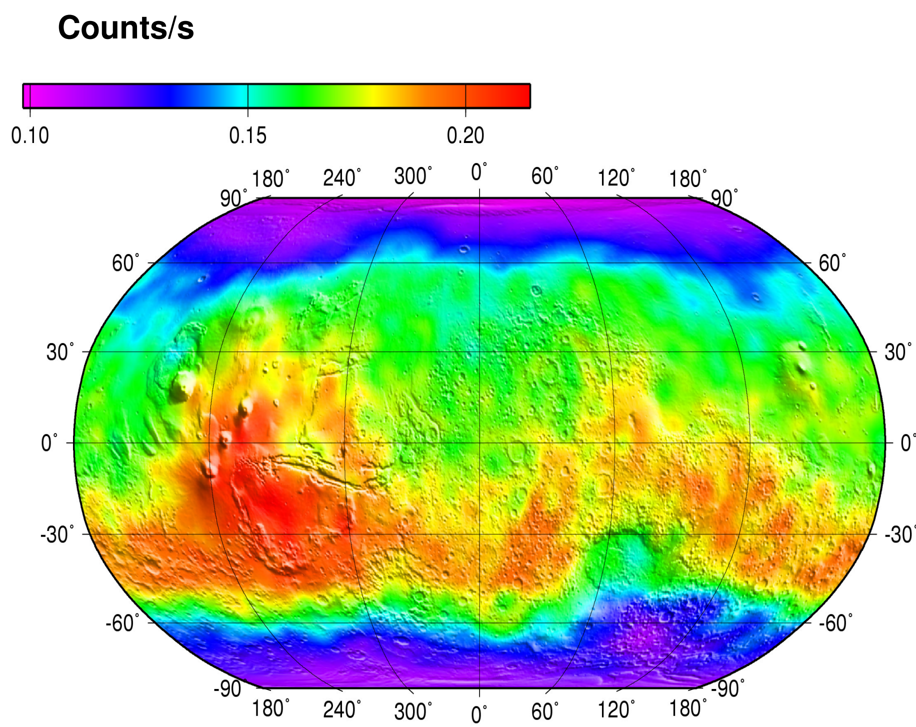




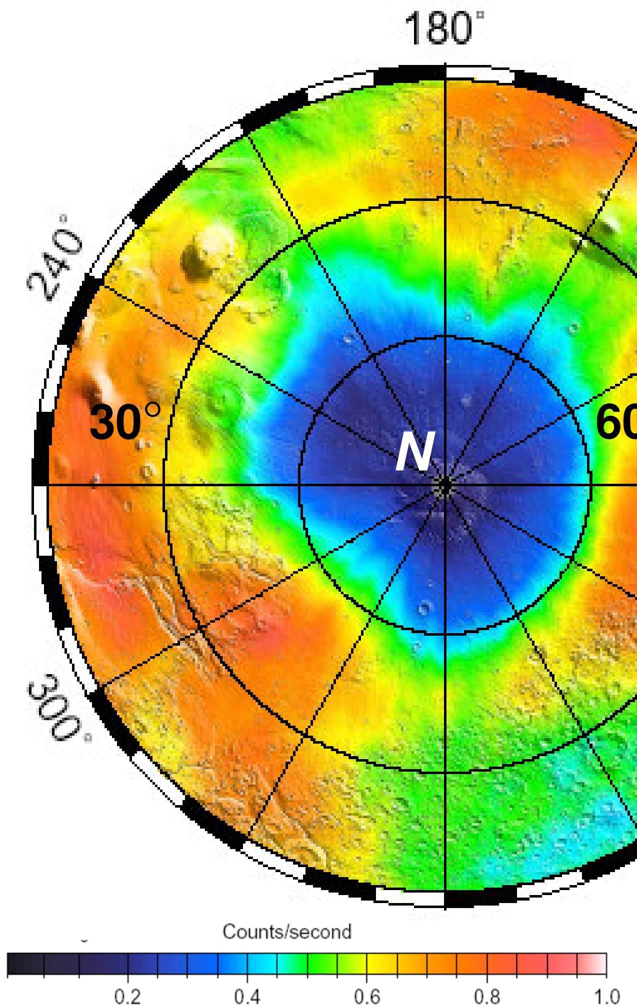
HEND (High Energy Neutron Detector) was developed in Space Research Institute (IKI RAN). It includes 5 detectors for registration of neutrons and gamma radiation in different energy bands

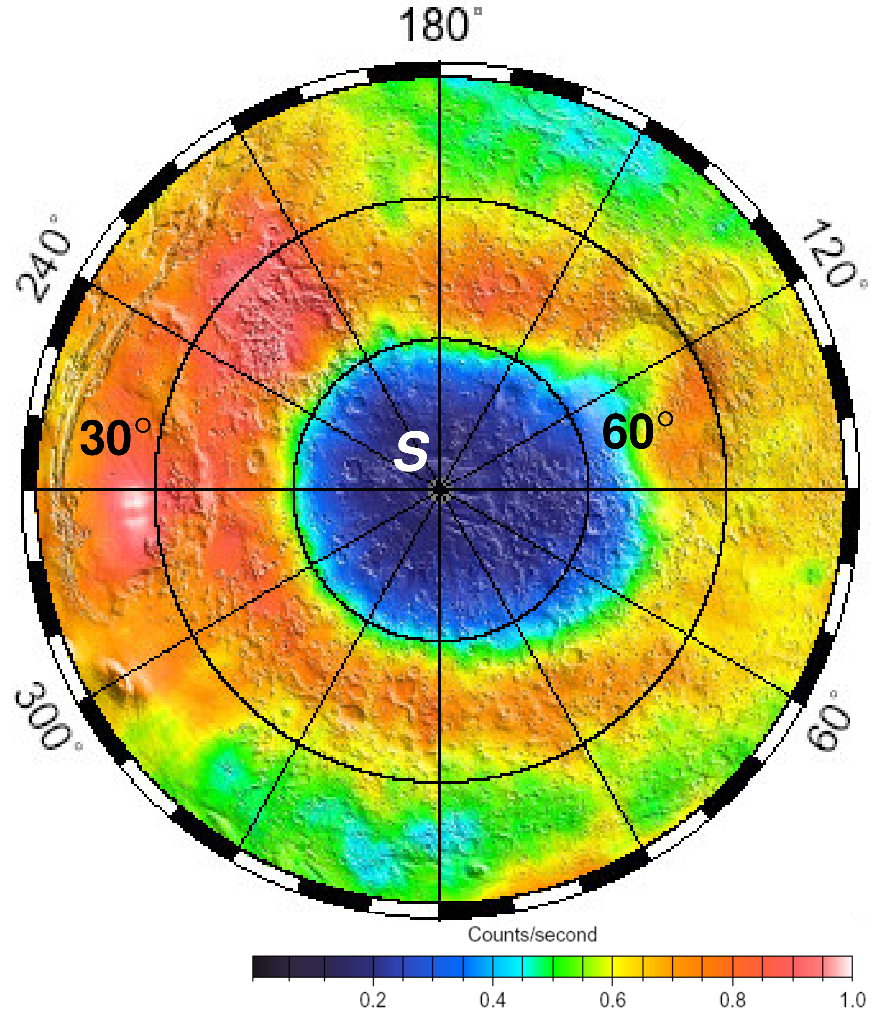
Summer-time map of epithermal neutrons (left) and high energy neutrons > 2MeV (right) according to HEND/Odyssey data





HEND epithermal neutrons for Northern (left) and Southern (right) hemisphere





Set of three discovery papers in Science, May 2002

Sciencexpress Report

Distribution of Hydrogen in the Near-Surface of Mars: Evidence for Subsurface Ice Deposits

W. V. Boynton,[1]* W. C. Feldman,[2] S. W. Squyres,[3] T. Prettyman,[2] J. Brückner,[4] L. G. Evans,[5] R. C. Reedy,[2,6] R. Starr,[7] J. R. Arnold,[8] D. M. Drake,[9] P. A. J. Englert,[10] A. E. Metzger,[11] Igor Mitrofanov,[12] J. I. Trombka,[13] C. d'Uston,[14] H. Wänke,[4] O. Gasnault,[14] D. K. Hamara,[1] D. M. Janes,[1] R. L. Marcialis,[1] S. Maurice,[15] I. Mikheeva,[1] G. J. Taylor,[16] R. Tokar,[2] C. Shinohara[1]

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Research Institute
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Sciencexpress Report

Global Distribution of Neutrons from Mars: Results from Mars Odyssey

W. C. Feldman,[1]* W. V. Boynton,[2] R. L. Tokar,[1] T. H. Prettyman,[1] O. Gasnault,[1] S. W. Squyres,[3] R. C. Elphic,[1] D. J. Lawrence,[1] S. L. Lawson,[1] S. Maurice,[4] G. W. McKinney,[1] K. R. Moore,[1] R. C. Reedy[1]

[1]Los Alamos National Laboratory, Los Alamos, NM 87545, USA. [2]University of Arizona, Lunar Planetary Laboratory, Tucson, AZ 85721, USA. [3]Cornell University, Center for Radiophysics and Space Research, Ithaca, NY 14853, USA. [4]Observatoire Midi-Pyrénées, 31

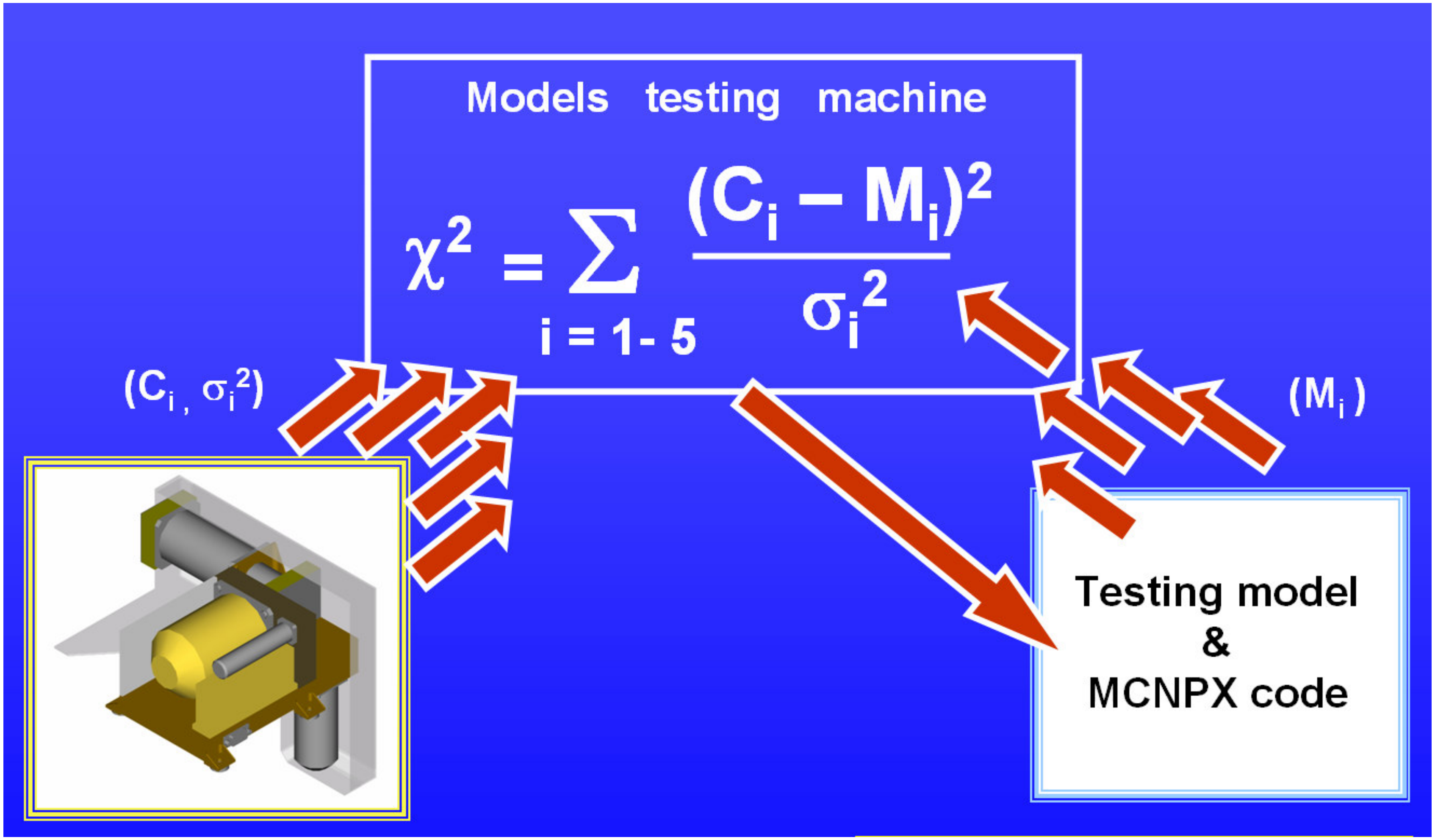
*To whom corresp

Sciencexpress Report

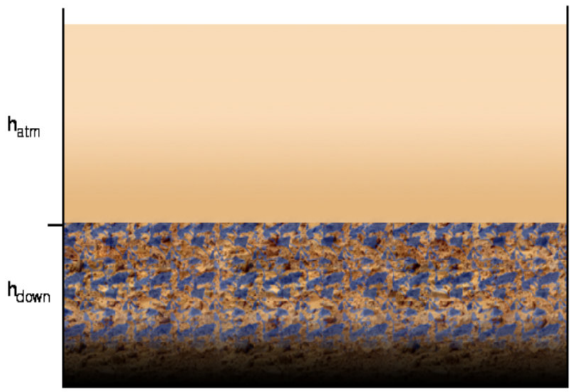
Maps of Subsurface Hydrogen from the High-Energy Neutron Detector, Mars Odyssey

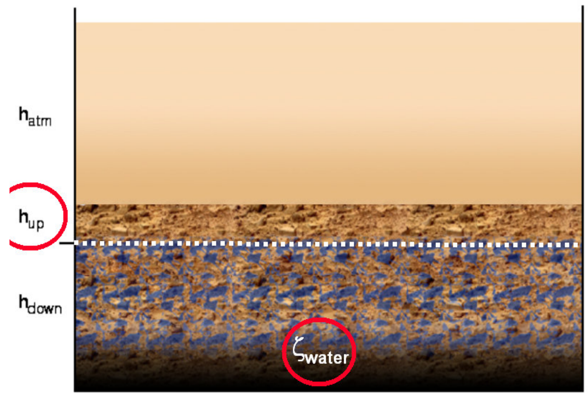
I. Mitrofanov,[1] D. Anfimov,[1] A. Kozyrev,[1] M. Litvak,[1] A. Sanin,[1] V. Tret'yakov,[1] A. Krylov,[2] V. Shvetsov,[2] W. Boynton,[3] C. Shinohara,[3] D. Hamara,[3] R. S. Saunders[4]

[1]Institute for Space Research, Moscow 117997, Russia. [2]Joint Institute for Nuclear Research, Dubna 141980, Russia. [3]University of Arizona, Tucson, AZ 85721, USA. [4]Jet Propulsion Laboratory, Pasadena, CA 91109, USA.


Models testing machine
$$\chi^2 = \sum_{i=1-5} \frac{(C_i - M_i)^2}{\sigma_i^2}$$
(C_i, σ_i^2)
(M_i)
Testing model
&
MCNPX code

Northern *Absolute Minimum Spot*: 24°-28°E, 86°-90°N



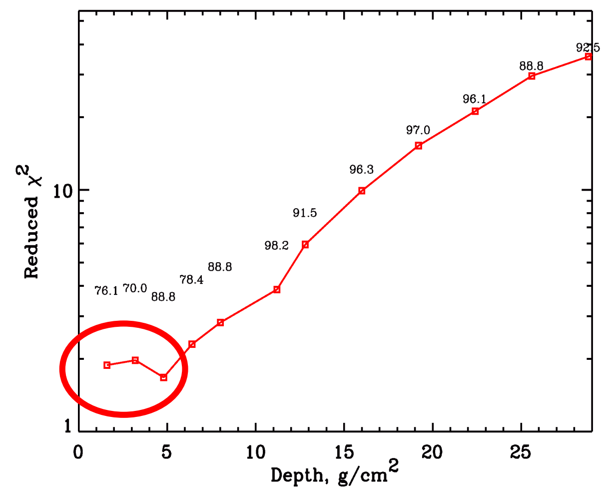


Homogeneous Model (HM):

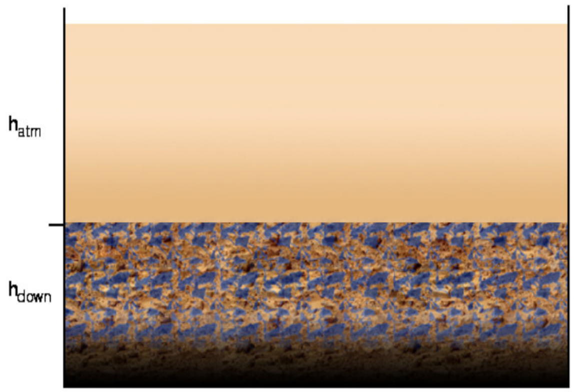
ζ_{water} = 63 wt %

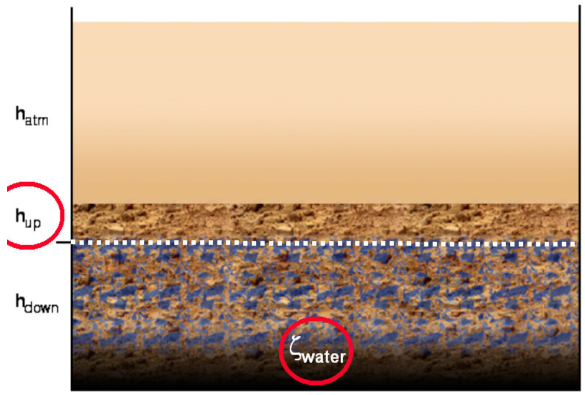
with good acceptance probability

Double-layered Model DLM):



Southern *Absolute Minimum Spot*: 220°-224°E, 76°-80°N





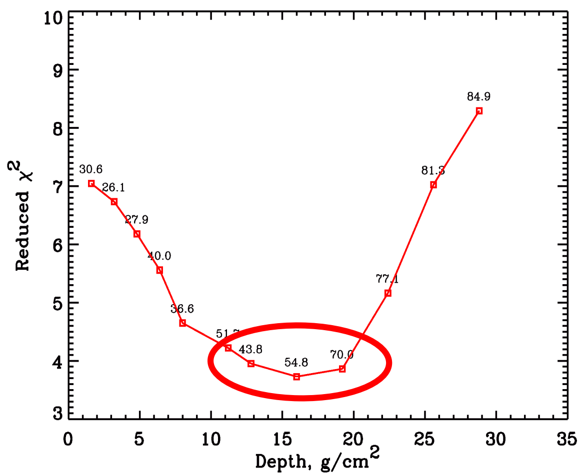
<u>Homogeneous Model</u> (HM):

ζ_{water} = 25 wt %

with very acceptance probability

P < 10^{-4}

<u>Double-layered Model (DLM):</u>



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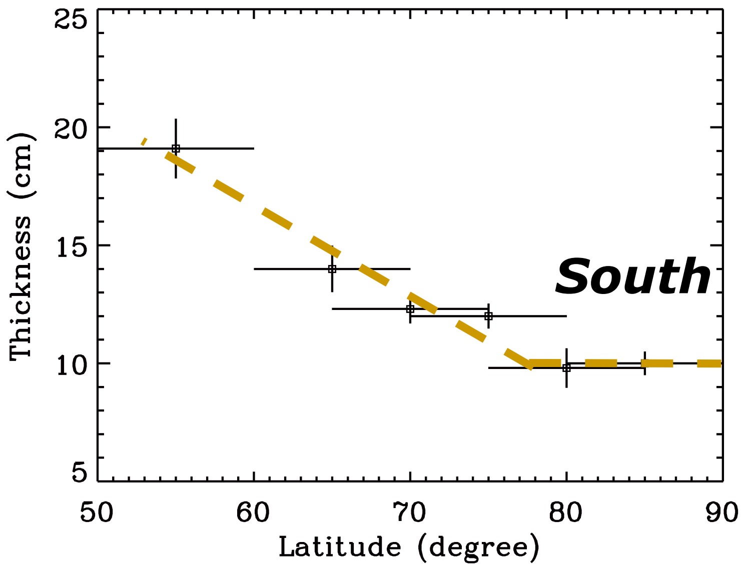
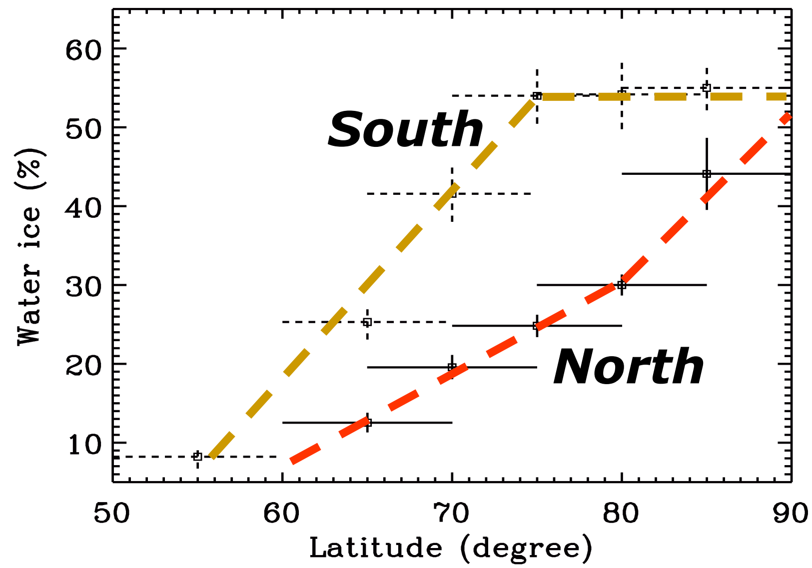


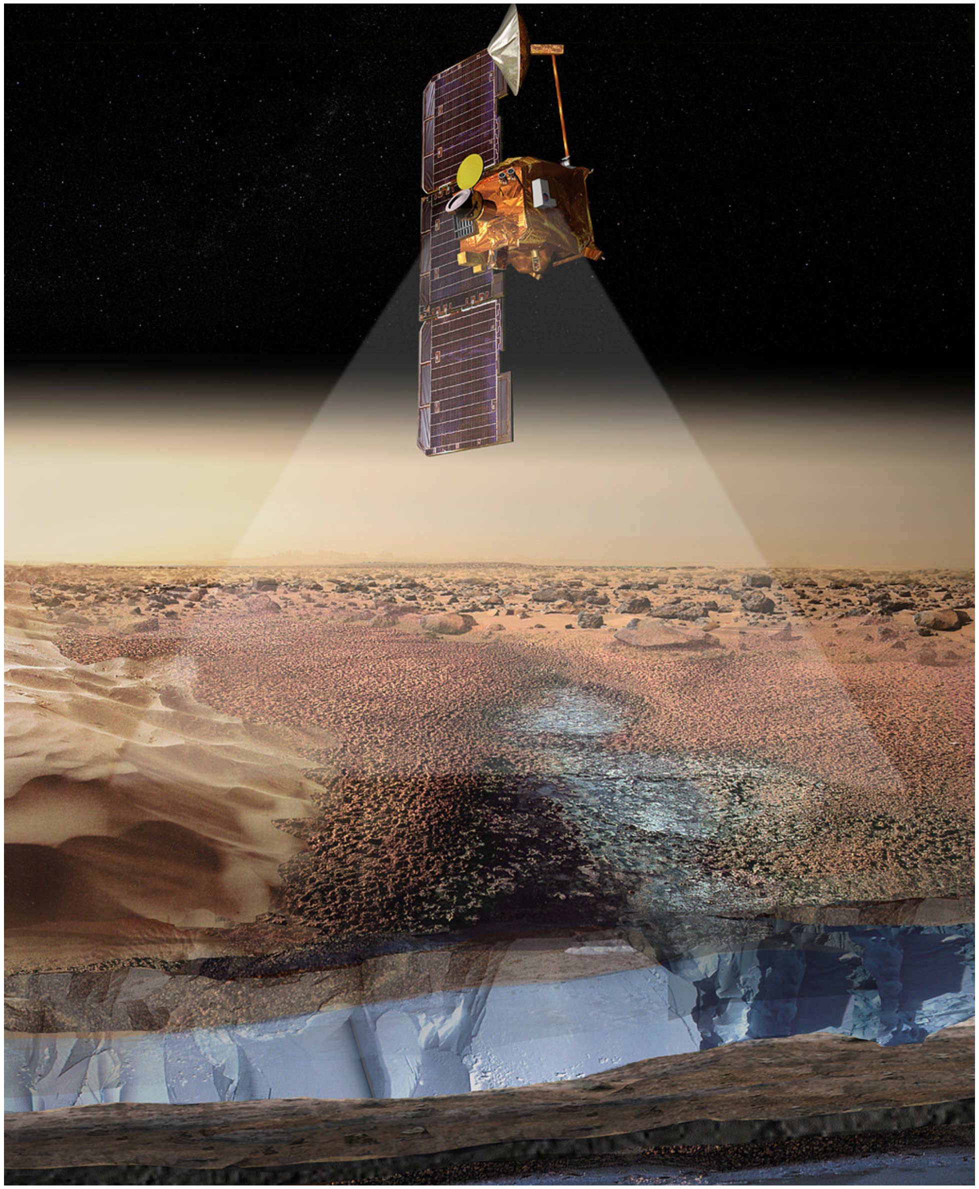


Selected Latitude Belt	Latitudes	Acceptable Model of Subsurface	
Northern Polar Region	>80º N	HM, no dry top layer:	44.1 wt%
Northern High Latitude Belt	70°-80° N	HM, no dry top layer:	24.8 wt%
Northern Boundary Belt	60°-70° N	HM, no dry top layer:	12.5 wt%
Southern Polar Region	>80° S	DLM with dry top layer:	55.0 wt% under 16.0 g/cm^2
Southern High Latitude Belt	70°-80° S	DLM with dry top layer:	54.0 wt% under 19.2 g/cm^2
Southern Boundary Belt	60°-70° S	DLM with dry top layer:	25.3 wt% under 22.4 g/cm^2

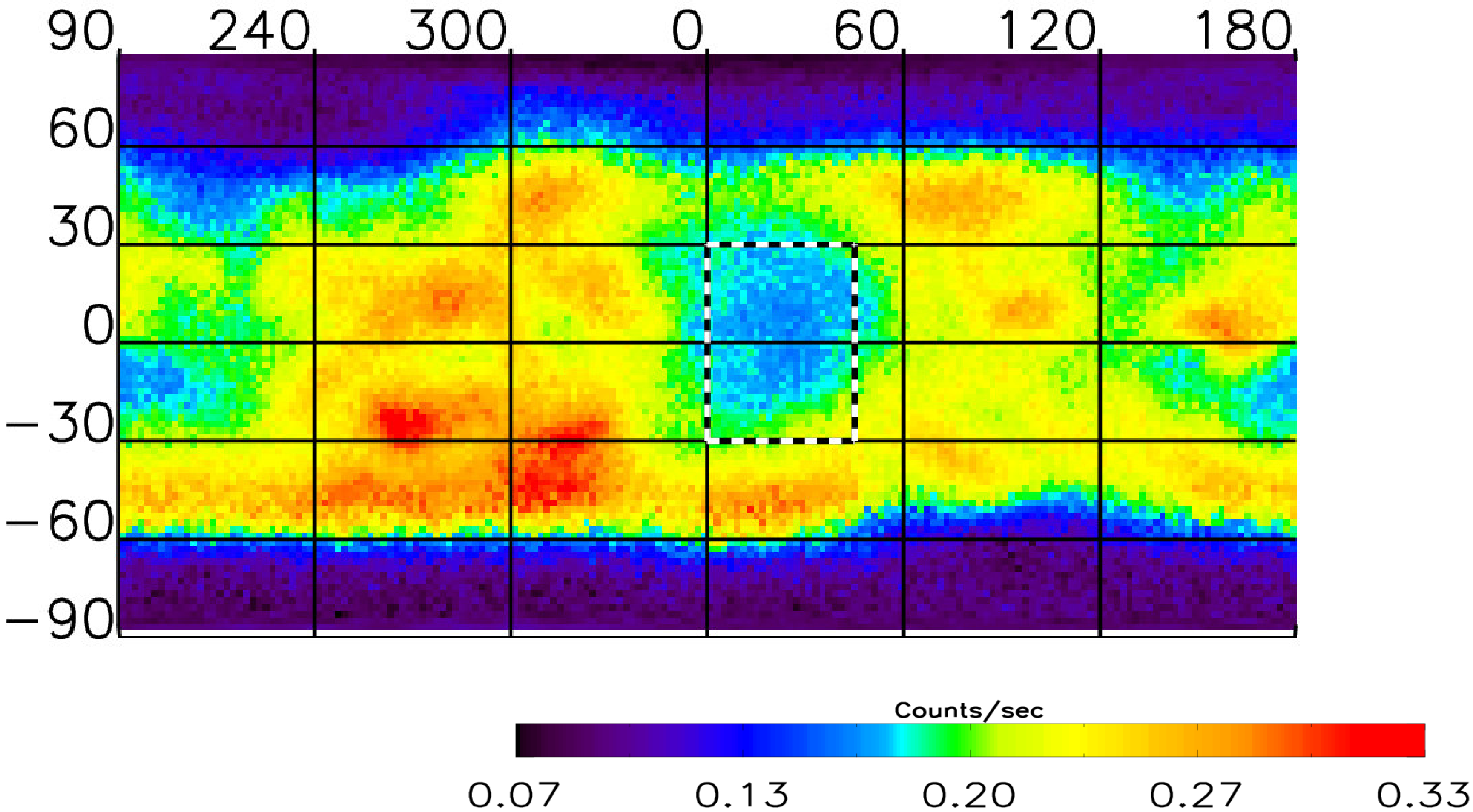
“Mars Odyssey” result:

Mars has northern and southern polarward permafrost regions above 50 – 60 degree of latitude with very high content of water ice in the soil –

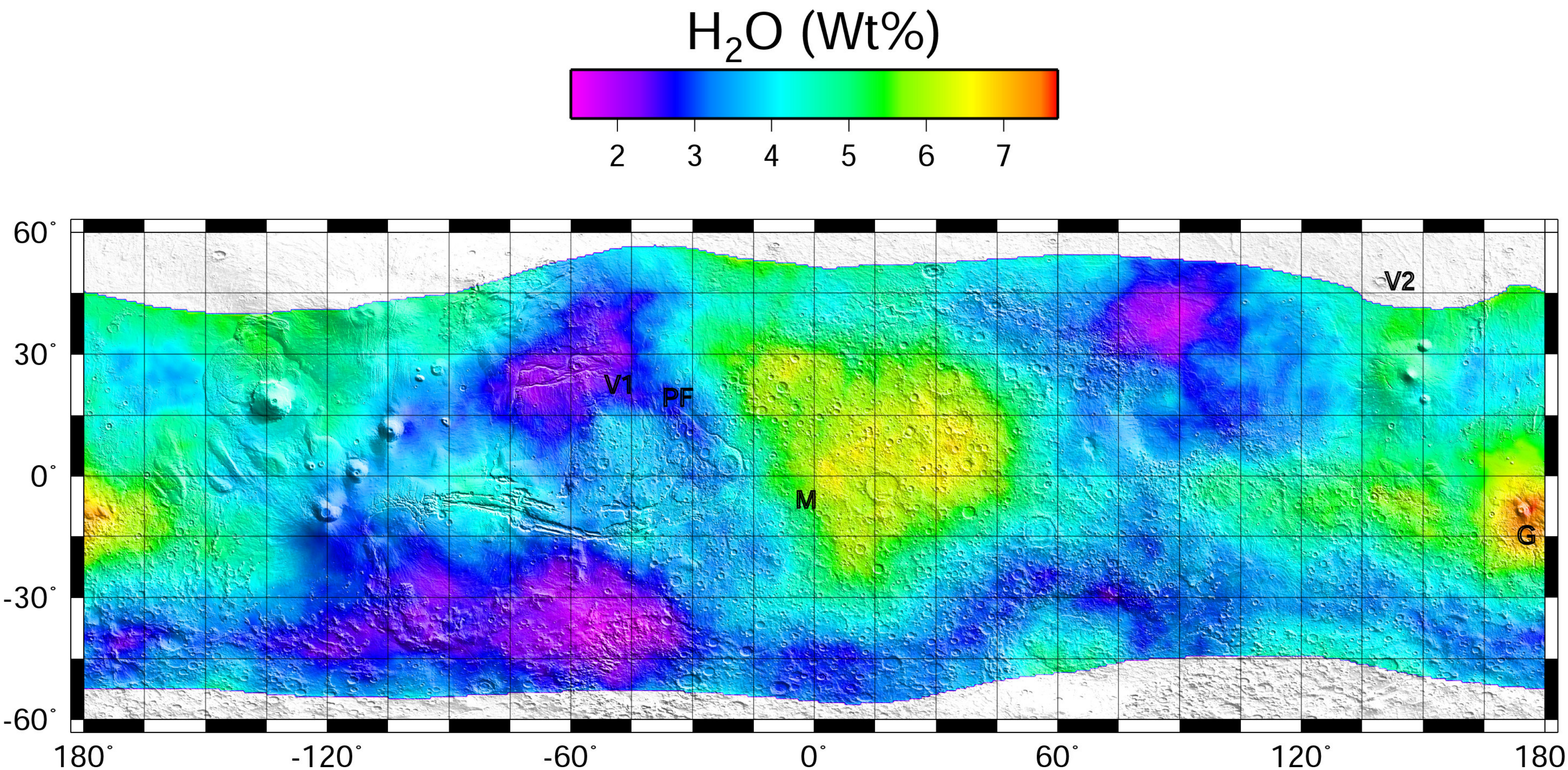
- *Dirty Water Ice* below the thin layer of dry regolith is the subject of investigation for future NASA “Phoenix” scout mission.



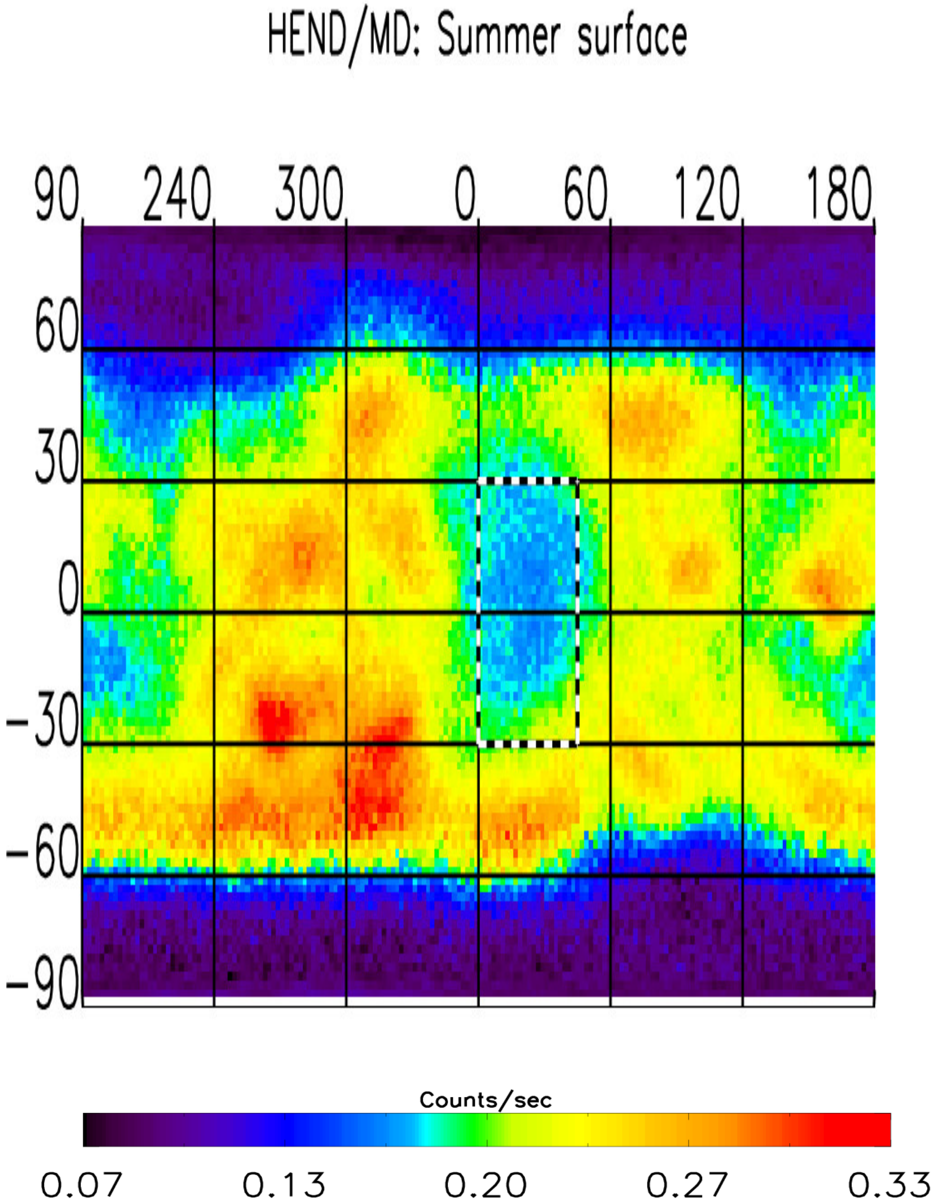
“Mars Odyssey” mystery – Arabia and Memnonia

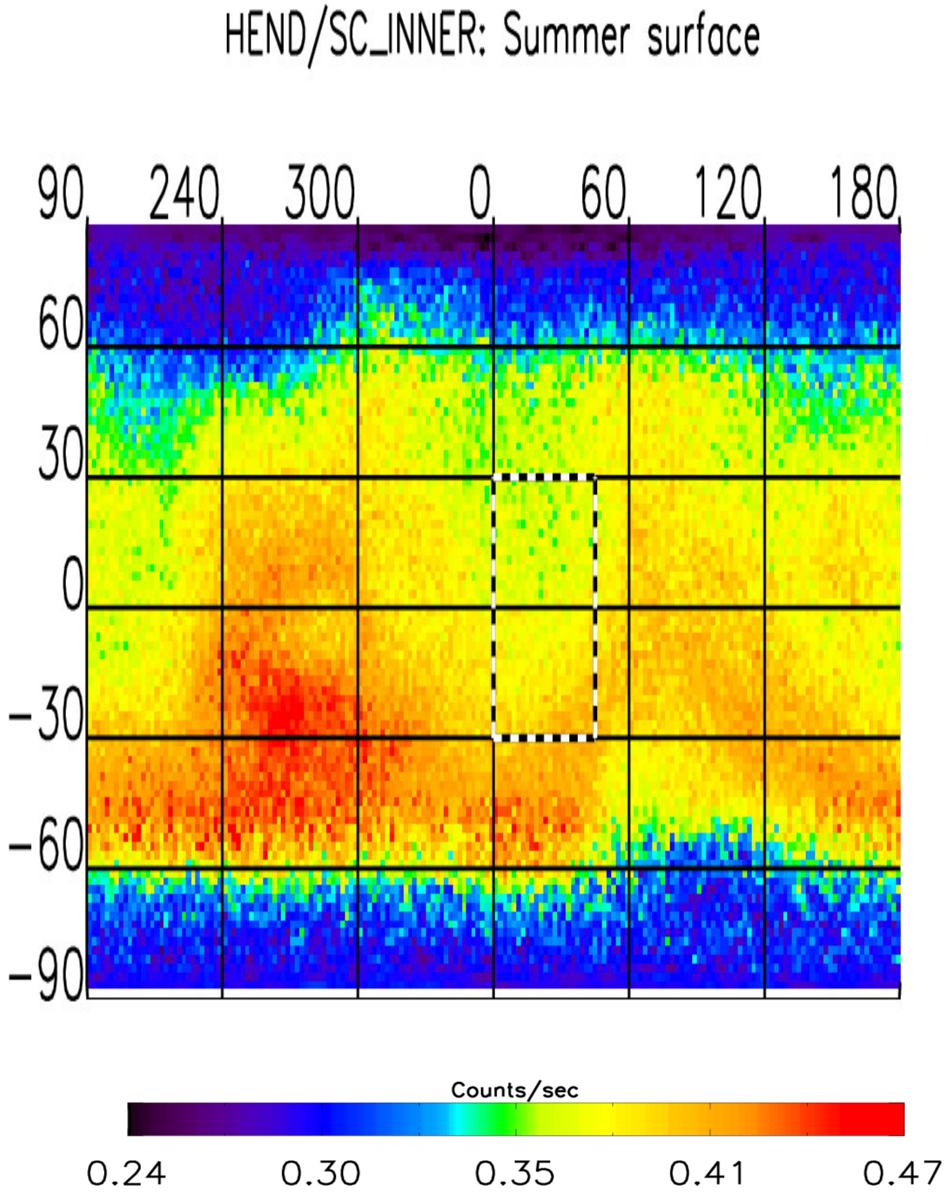


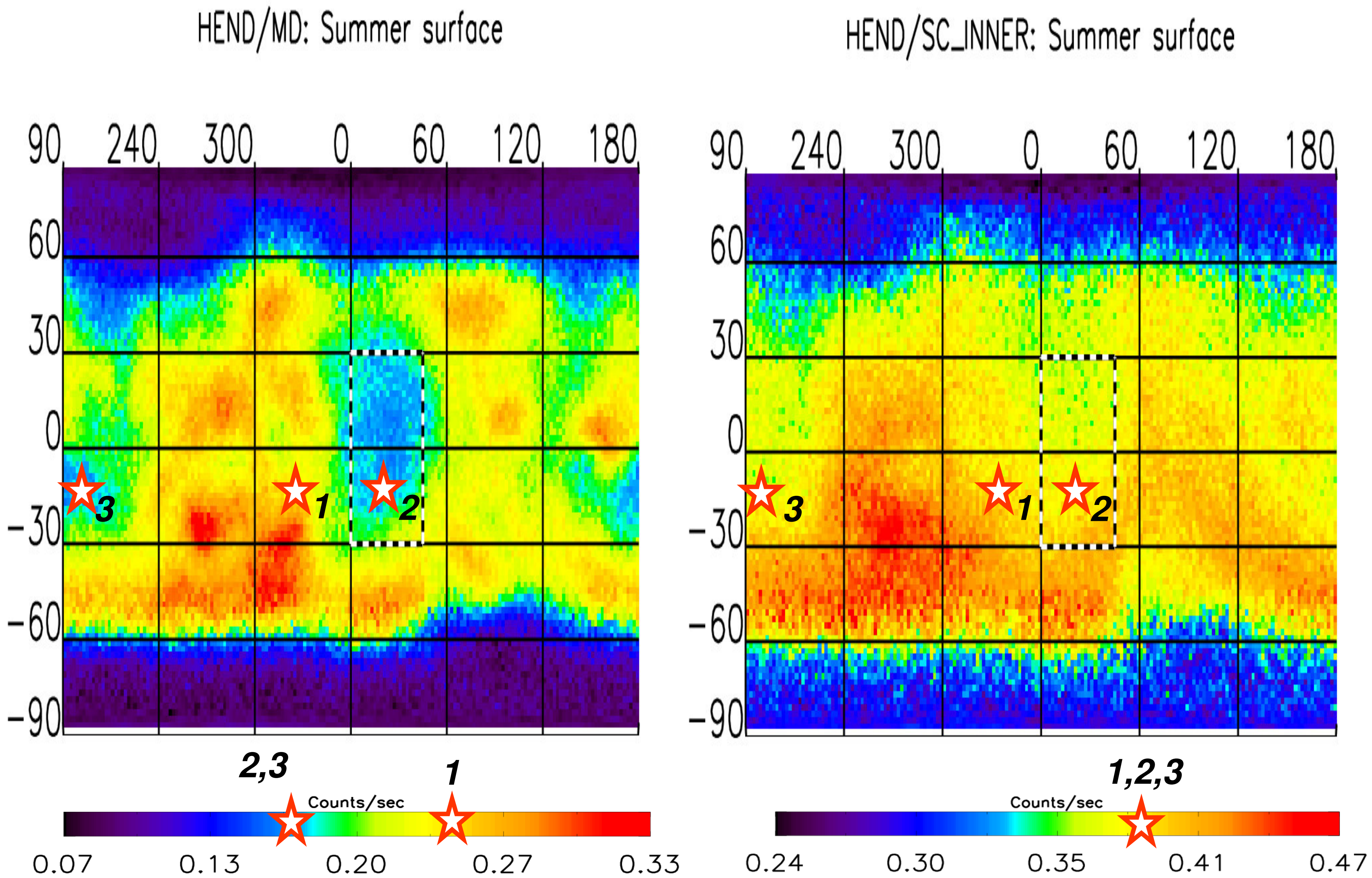
Arabia and Memnonia as seen by GRS at 2.2 MeV line



NSSTC – Special Seminar

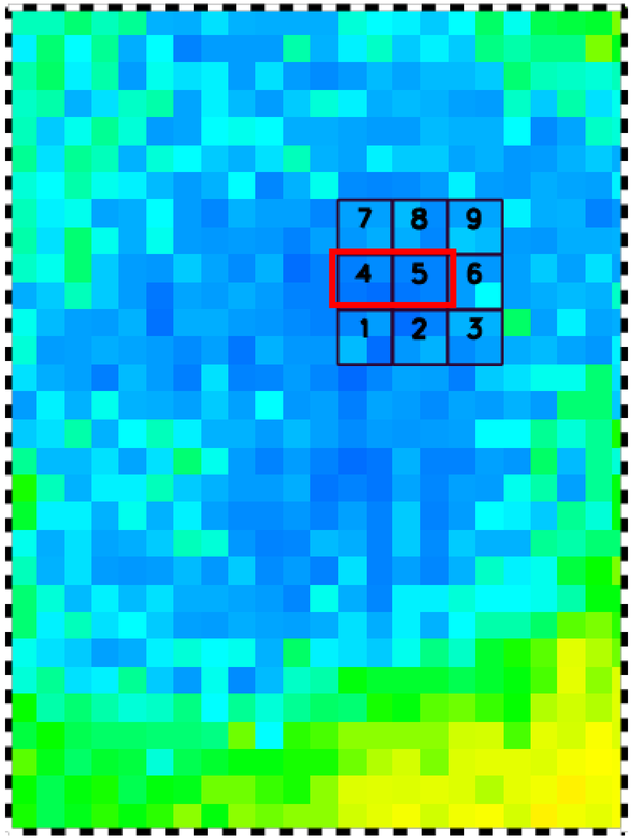





HEND/MD: Summer surface
HEND/SC_INNER: Summer surface
90 240 300 0 60 120 180
60
30
0
-30
-60
-90
3
1
2
2,3
1
1,2,3
Counts/sec
0.07 0.13 0.20 0.27 0.33
0.24 0.30 0.35 0.41 0.47

HEND/MD: Summer surface (Arabia)

Dynamic scale of epithermal neutron flux variations at Arabia is about 2, but there is no variations at MeV neutrons in this region



1: lon=[24,28], lat=[4,8] 0.168 cts

2: lon=[28,32], lat=[4,8] 0.167 cts

3: lon=[32,36], lat=[4,8] 0.172 cts

4: lon=[24,28], lat=[8,12] 0.163 cts

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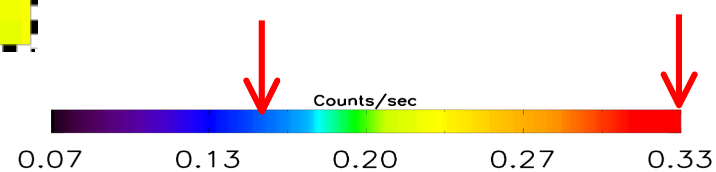
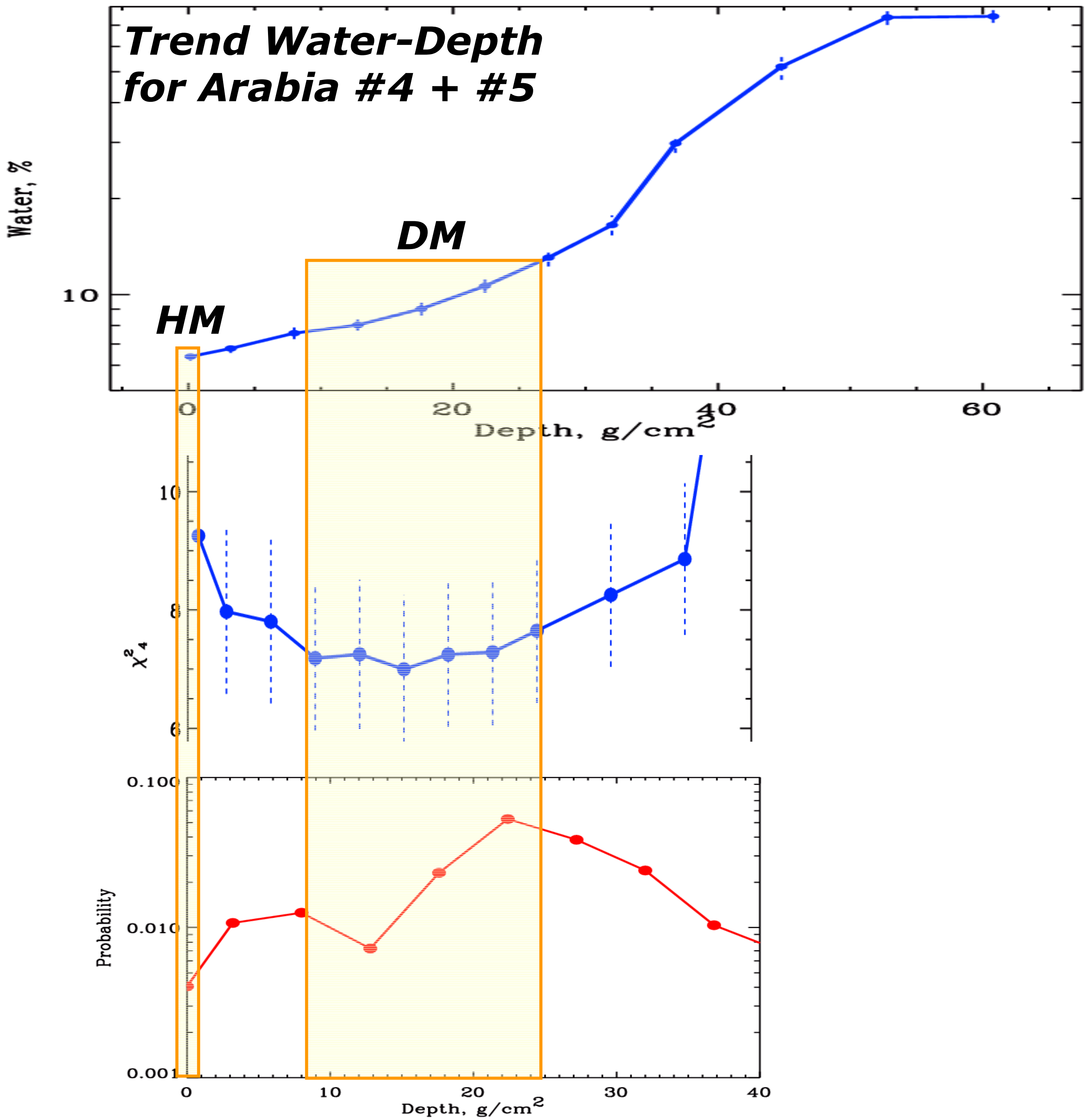
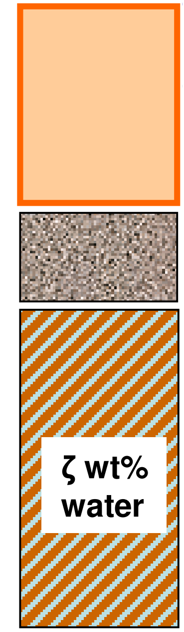
9: lon=[32,36], lat=[12,16] 0.175 cts



Xi² test

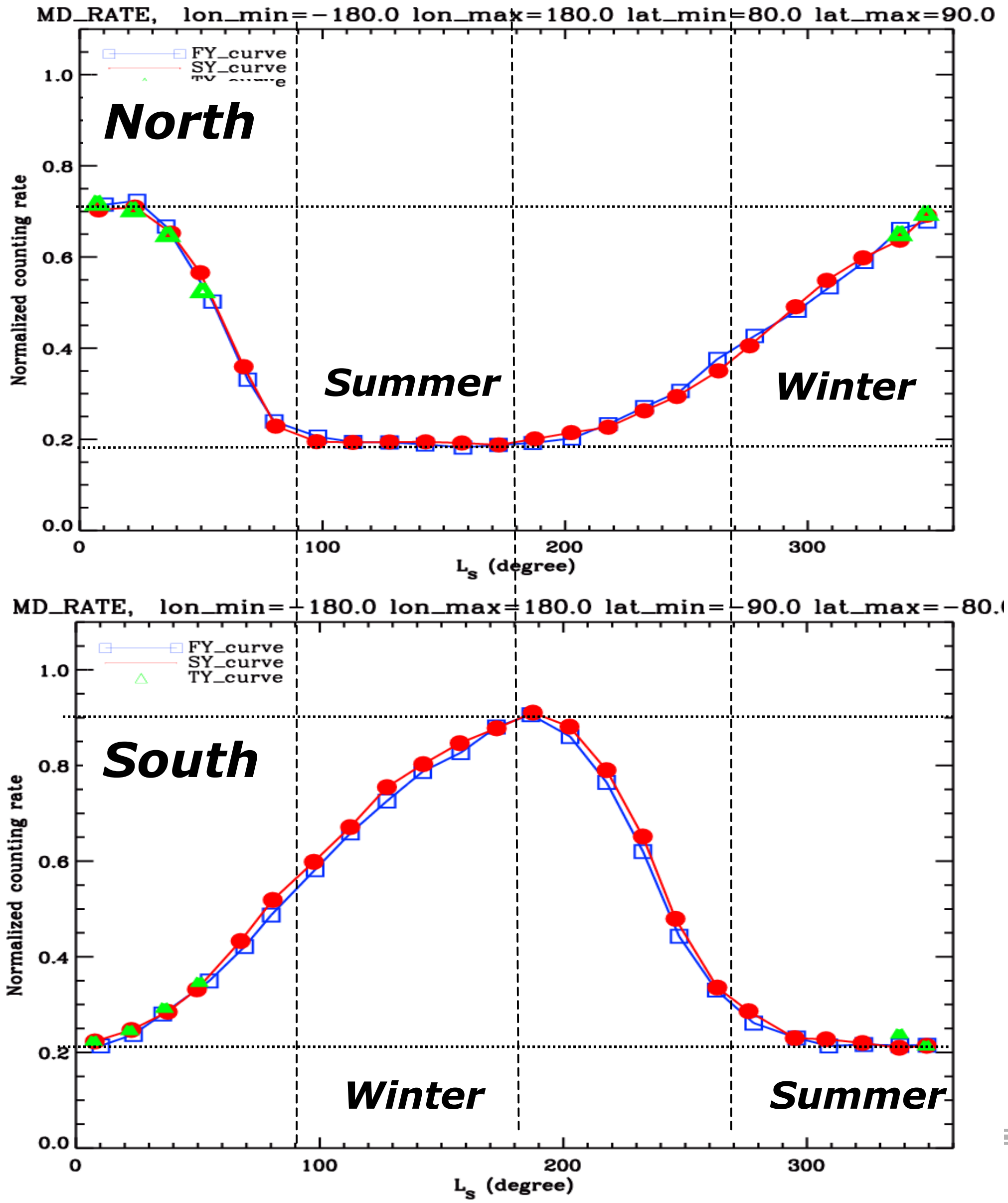
K-S test





ζ wt%
water

"Mars Odyssey" is measuring the 3rd Martian year in E1 - E2



Science, vol. 300, June 27, 2003

CO_2 Snow Depth and Subsurface Water-Ice Abundance in the Northern Hemisphere of Mars

I. G. Mitrofanov,[1*] M. T. Zuber,[2] M. L. Litvak,[1] W. V. Boynton,[3] D. E. Smith,[4] D. Drake,[5] D. Hamara,[3] A. S. Kozyrev,[1] A. B. Sanin,[1] C. Shinohara,[3] R. S. Saunders,[6] V. Tretyakov[1]

Observations of seasonal variations of neutron flux from the high-energy neutron detector (HEND) on Mars Odyssey combined with direct measurements of the thickness of condensed carbon dioxide by the Mars Orbiter Laser Altimeter (MOLA) on Mars Global Surveyor show a latitudinal dependence of northern winter deposition of carbon dioxide. The observations are also consistent with a shallow substrate consisting of a layer with water ice overlain by a layer of drier soil. The lower ice-rich layer contains between 50 and 75 weight % water, indicating that the shallow subsurface at northern polar latitudes on Mars is even more water rich than that in the south.

Mars undergoes seasons in which volatile species, carbon dioxide (CO_2) and, to a much lesser extent, water are exchanged between the atmosphere and surface (*1*, *2*). The winter deposition in both hemispheres consists of con-

to estimate the water-ice content of the shallow subsurface at northern polar latitudes.

Nuclear emission from Mars is produced within the uppermost surface layer, where energetic charged particles of galactic cosmic

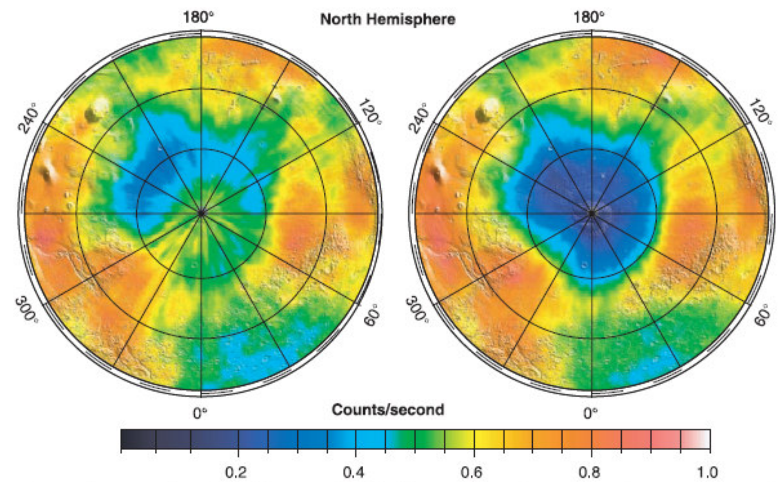


Fig. 1. Polar maps of epithermal neutron flux (*21*) from northern hemisphere of Mars as measured during northern winter (L_s = 330° to 360°) and summer (L_s = 100° to 165°) (*20*). The maps have a pixel resolution of 1° by 1° (60 km by 60 km) and have been smoothed with linear averaging in 5° by 5° cells (*40*). The count rate of the neutron flux has been normalized by its maximum value, which is observed in the equatorial Solis Planum region at 270°E, 25°S (*33*). The neutron flux is superposed on a shaded relief map of MOLA topography (*25*).

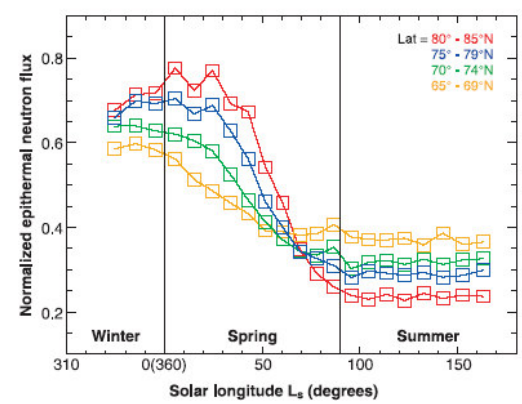
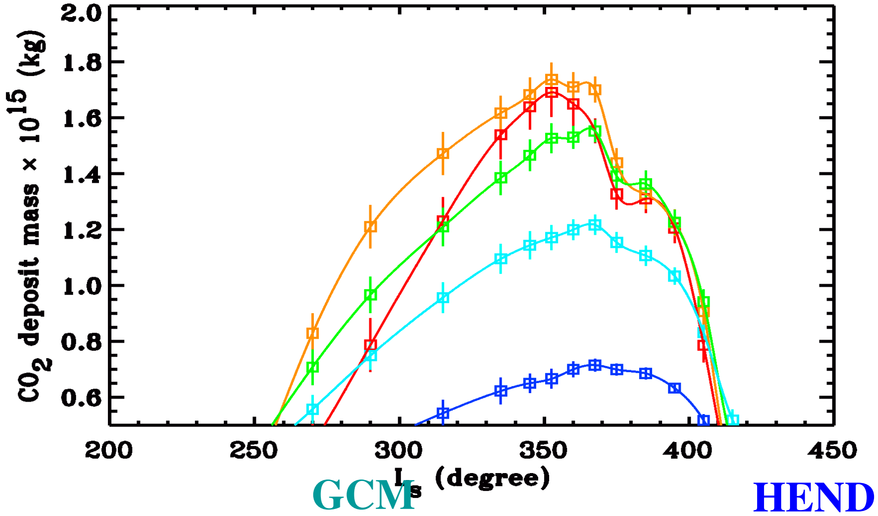


Fig. 2. Seasonal variation of average fluxes of epithermal neutrons for latitudinal annuli in the northern hemisphere: 80° to 85°N (red), 75° to 79°N (blue), 70° to 74°N (green), and 65° to 69°N (yellow). The normalized (*33*) neutron flux is shown by square symbols where the size of the symbol corresponds to the statistical error.

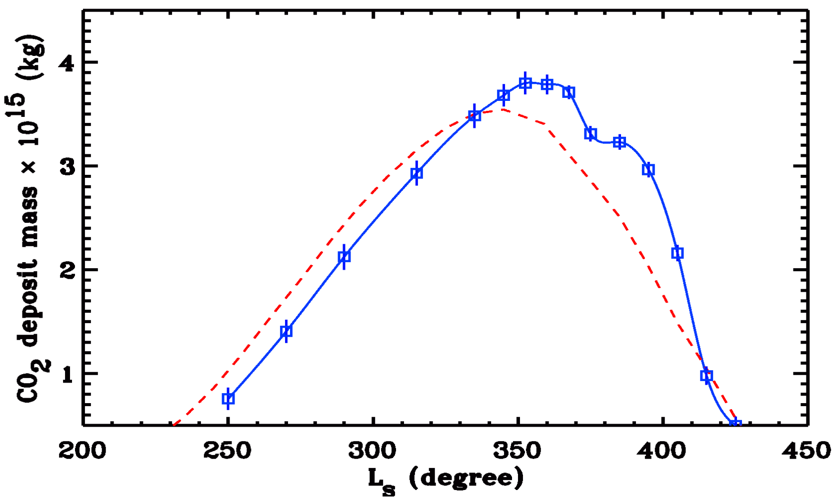
Mass of North Seasonal Cap of CO_2 *vs.* time

North latitude belts

80N – 90N
75N – 85N
70N – 80N
65N – 75N
60N – 70N



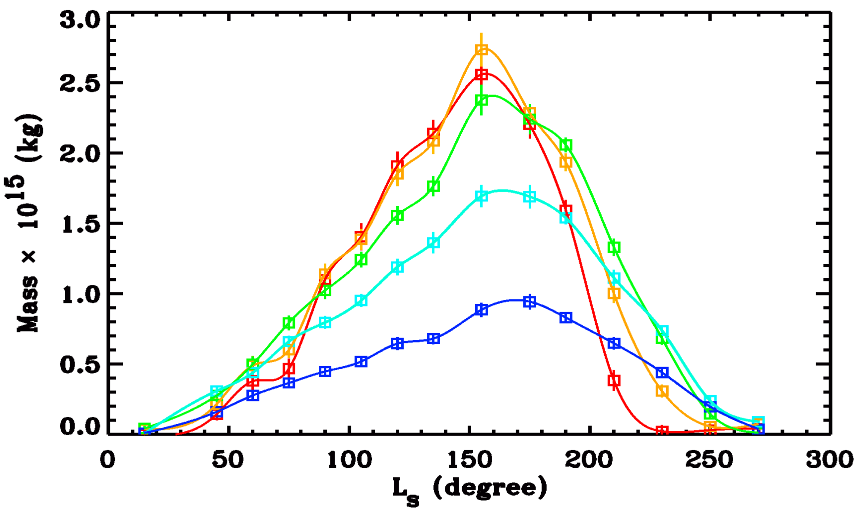
Total mass of North seasonal cap



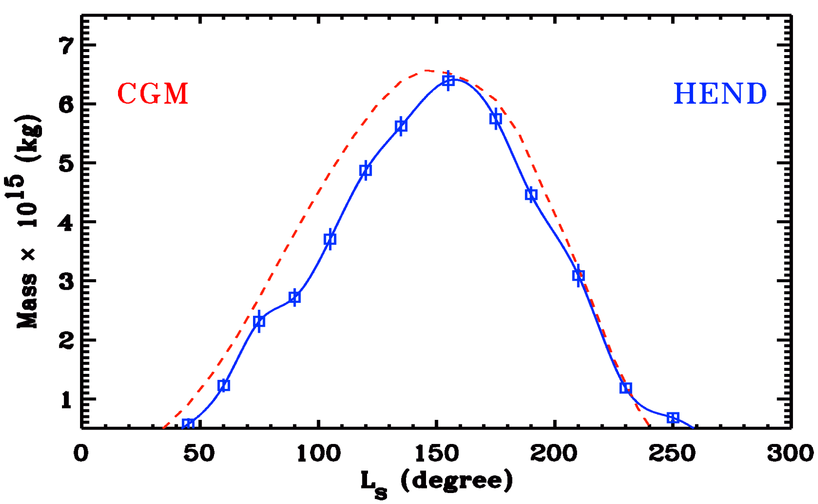
Mass of South Seasonal Cap of CO_2 *vs.* time

South latitude belts

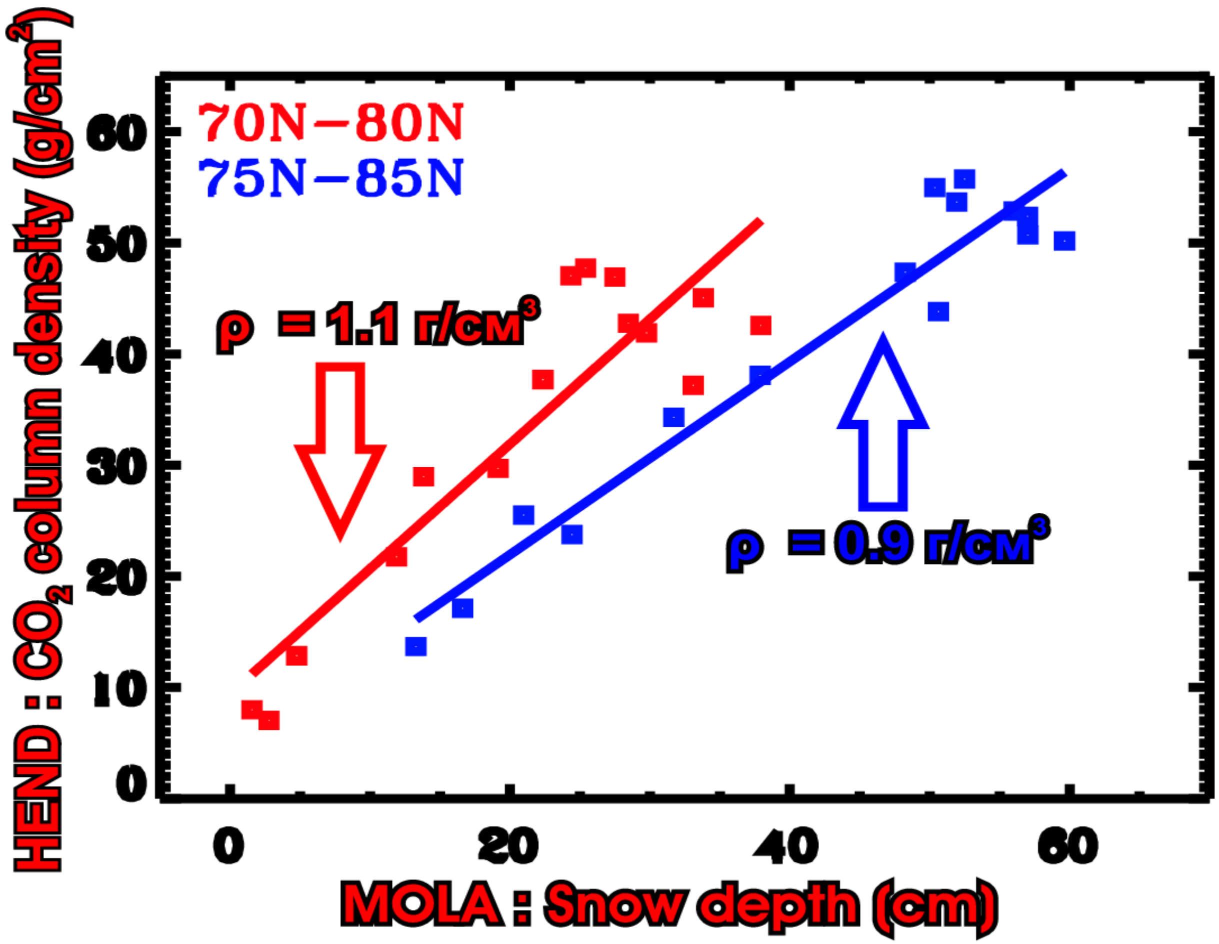
80S - 90S
75S - 85S
70S - 80S
65S - 75S
60S - 70S



Total mass of South seasonal cap



HEND data + MOLA data allowed to measure the density of CO_2 deposits



Even more science from "Mars Odyssey" – GRBs and SPEs

The Astrophysical Journal Supplement Series, 164:124-129, 2006 May

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Mars Odyssey Joins the Third Interplanetary Network

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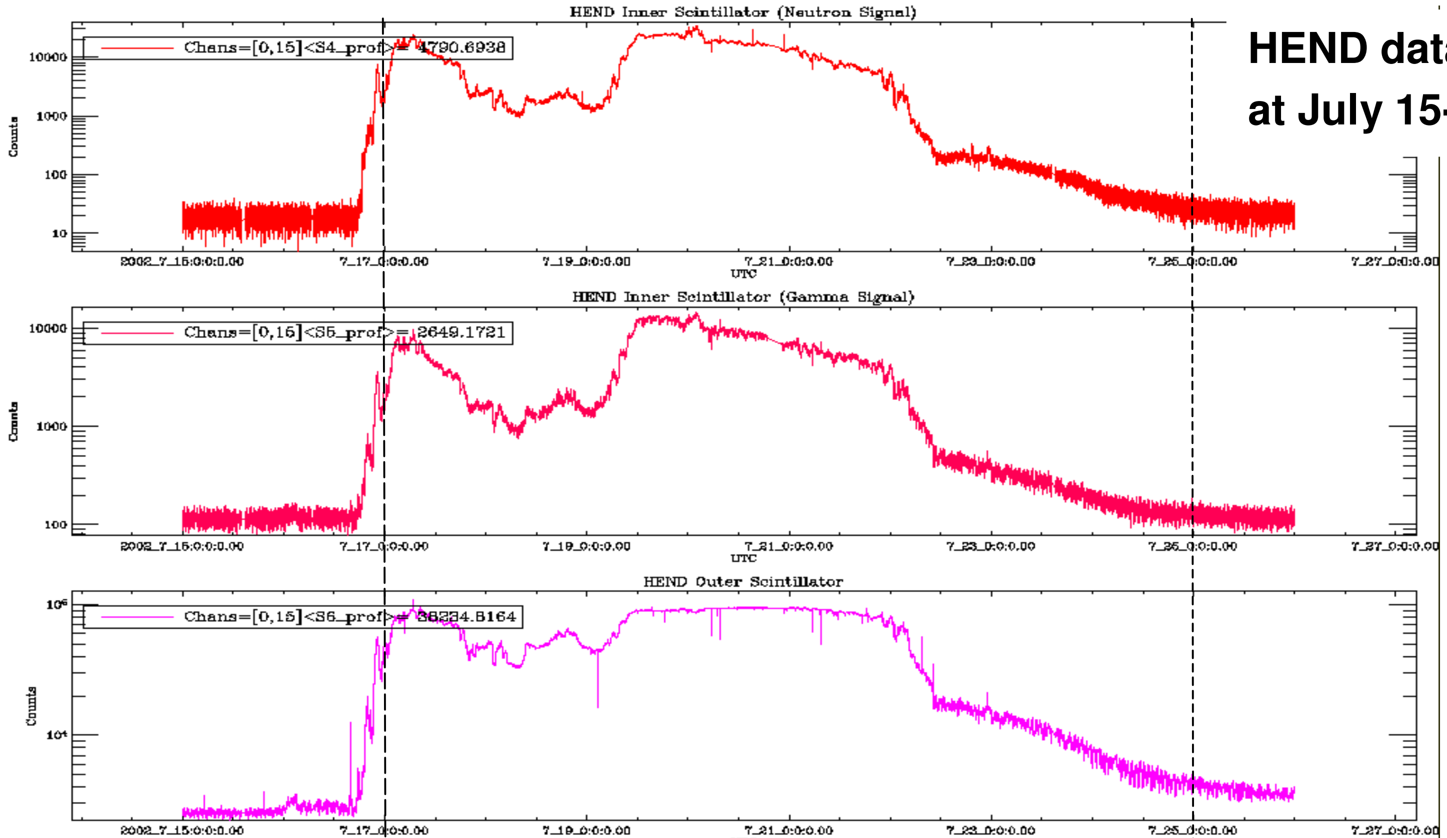
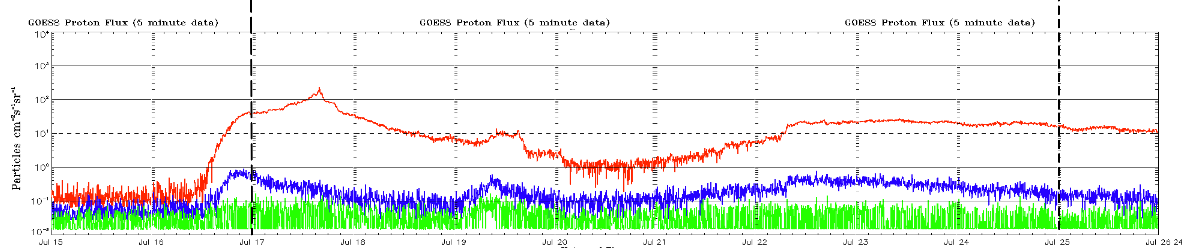
ABSTRACT
The *Mars Odyssey* spacecraft carries two experiments that are capable of detecting cosmic gamma-ray bursts and soft gamma repeaters. Since 2001 April they have detected over 275 bursts and, in conjunction with the other spacecraft of the interplanetary network, localized many of them rapidly and precisely enough to allow sensitive multiwavelength counterpart searches. We present the *Mars Odyssey* mission and describe the burst capabilities of the two experiments in detail. We explain how the spacecraft timing and ephemeris have been verified in-flight using bursts from objects whose precise positions are known by other means. Finally, we show several examples of localizations and discuss future plans for the *Odyssey* mission and the network as a whole.

Even more science from "Mars Odyssey" – GRBs and SPEs



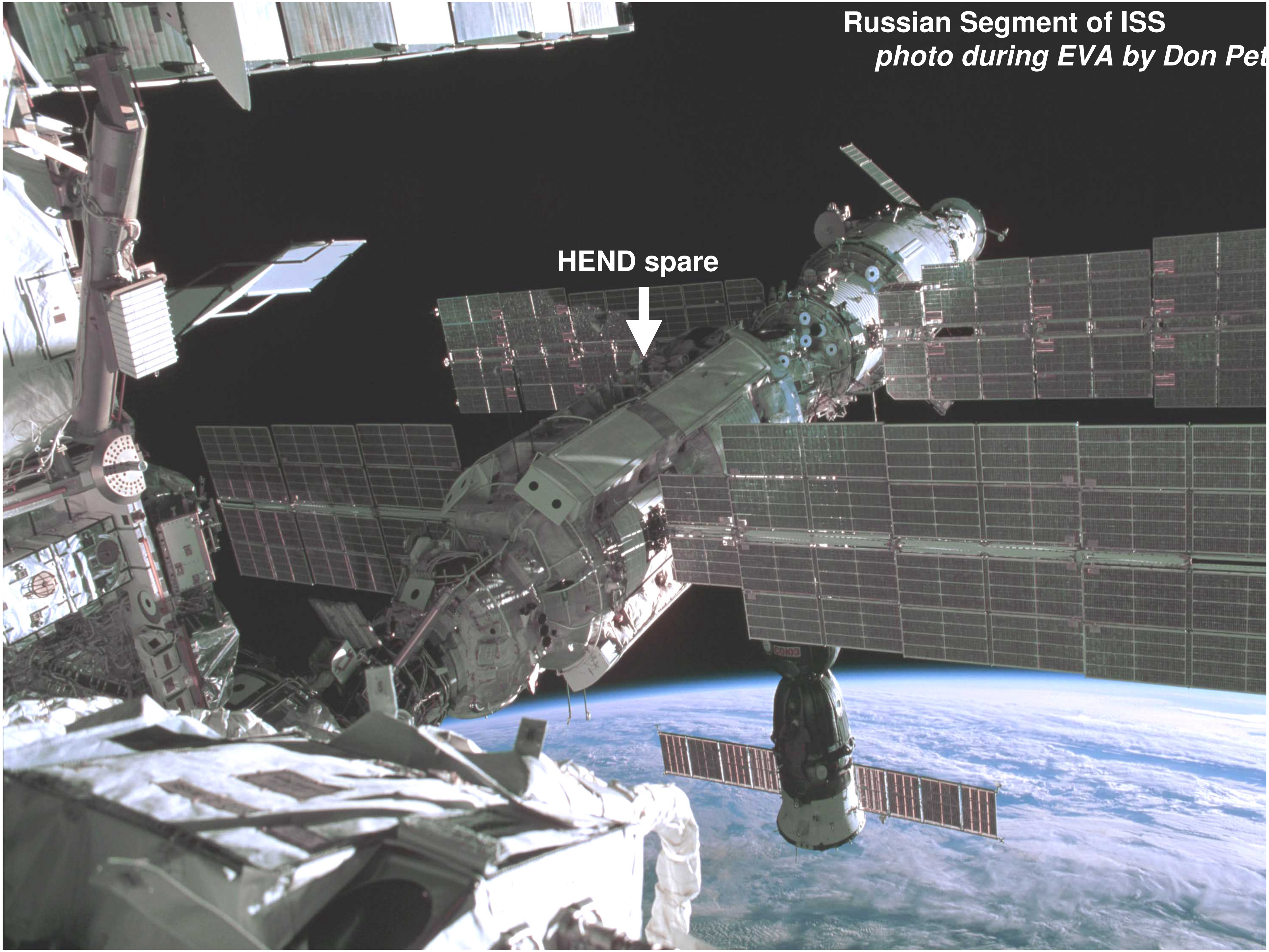
HEND data for SPE at July 15-27, 2002



GOES data for this SPE

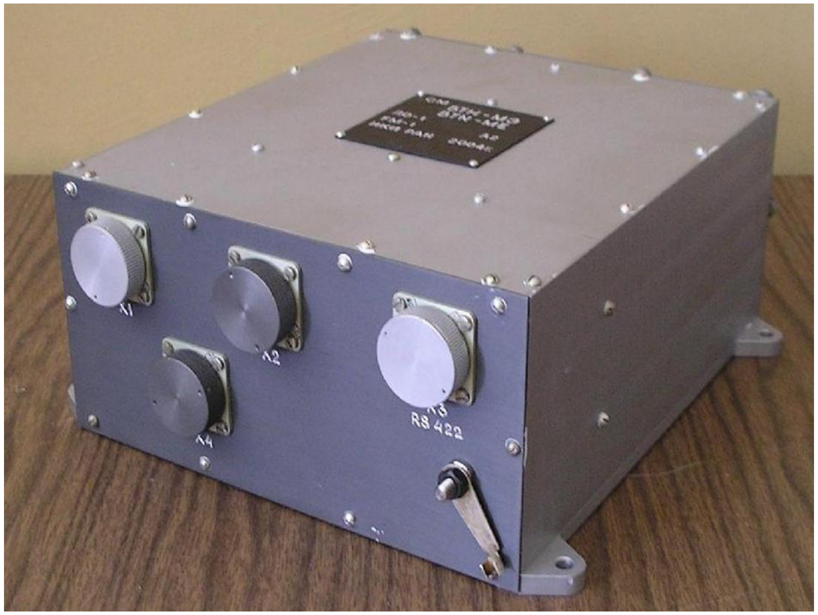
Experiment BTN on Russian Segment of ISS:

Spare Flight HEND go to ISS in October 2006


Russian Segment of ISS
photo during EVA by Don Pet
HEND spare

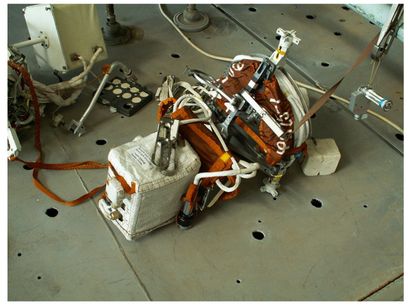
BTN (HEND spare) is scheduled for October 2006 (14^{th} ISS Expedition)

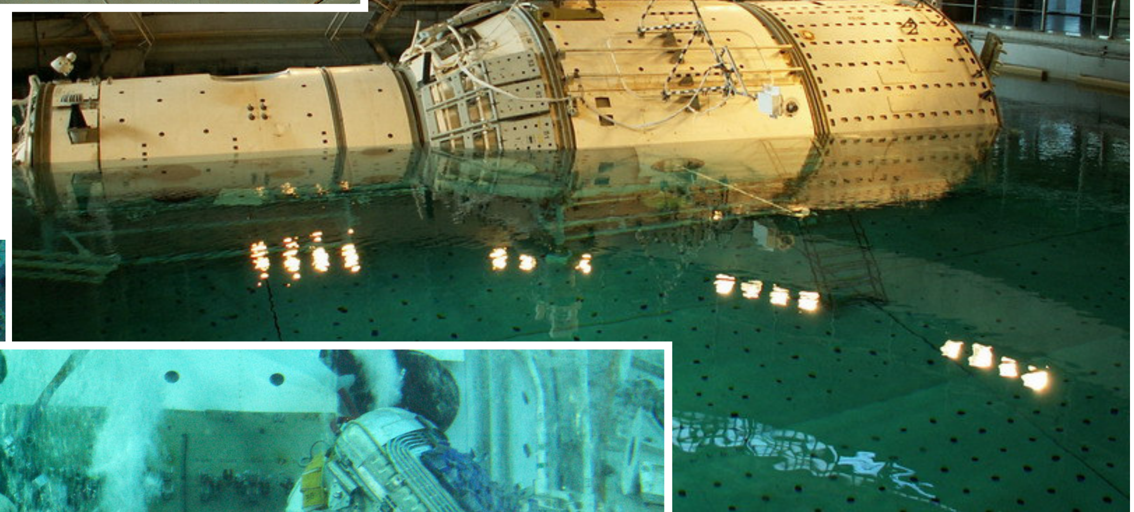
External detection module of BTN

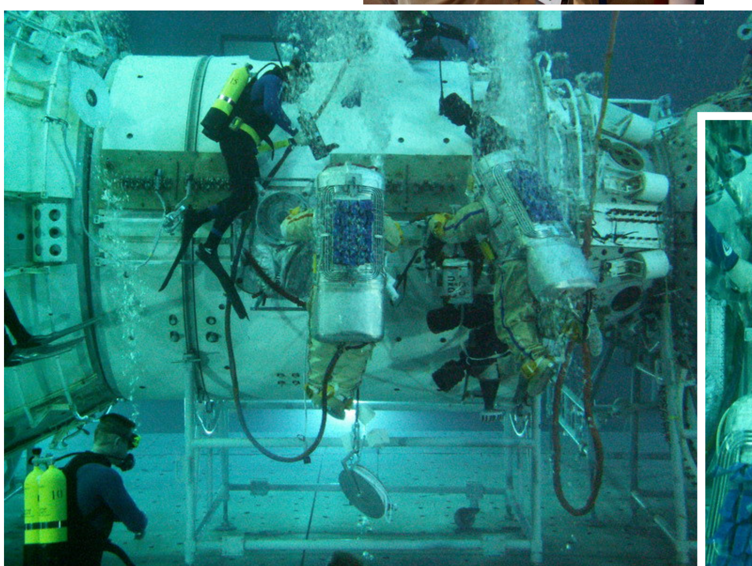


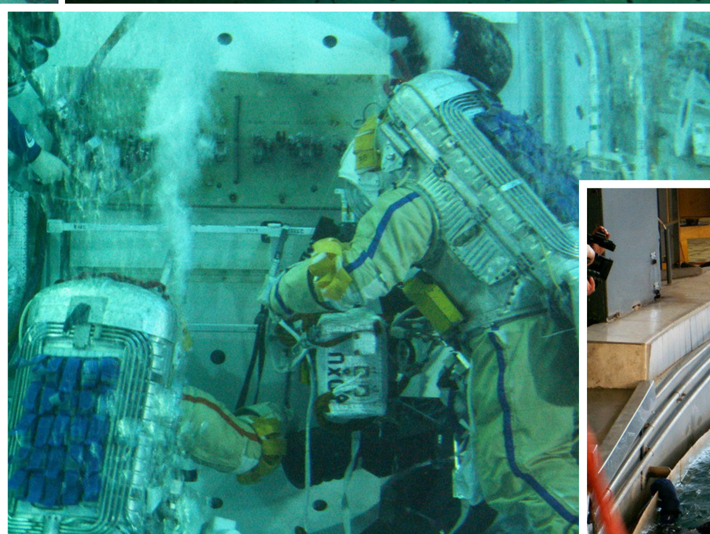
Internal interface module of BTN

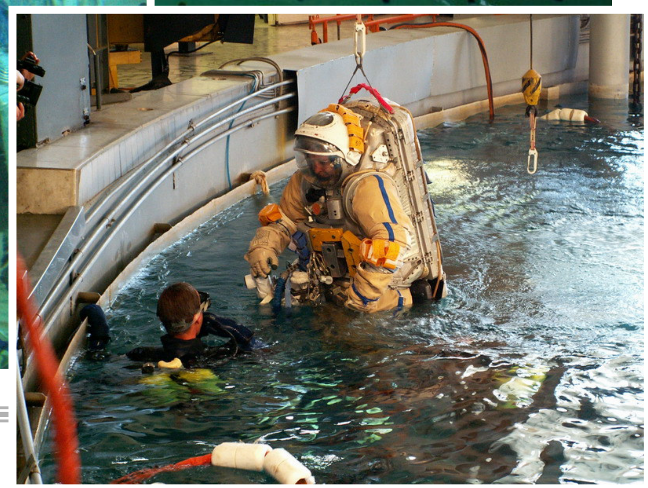
NSSTC – Special Seminar





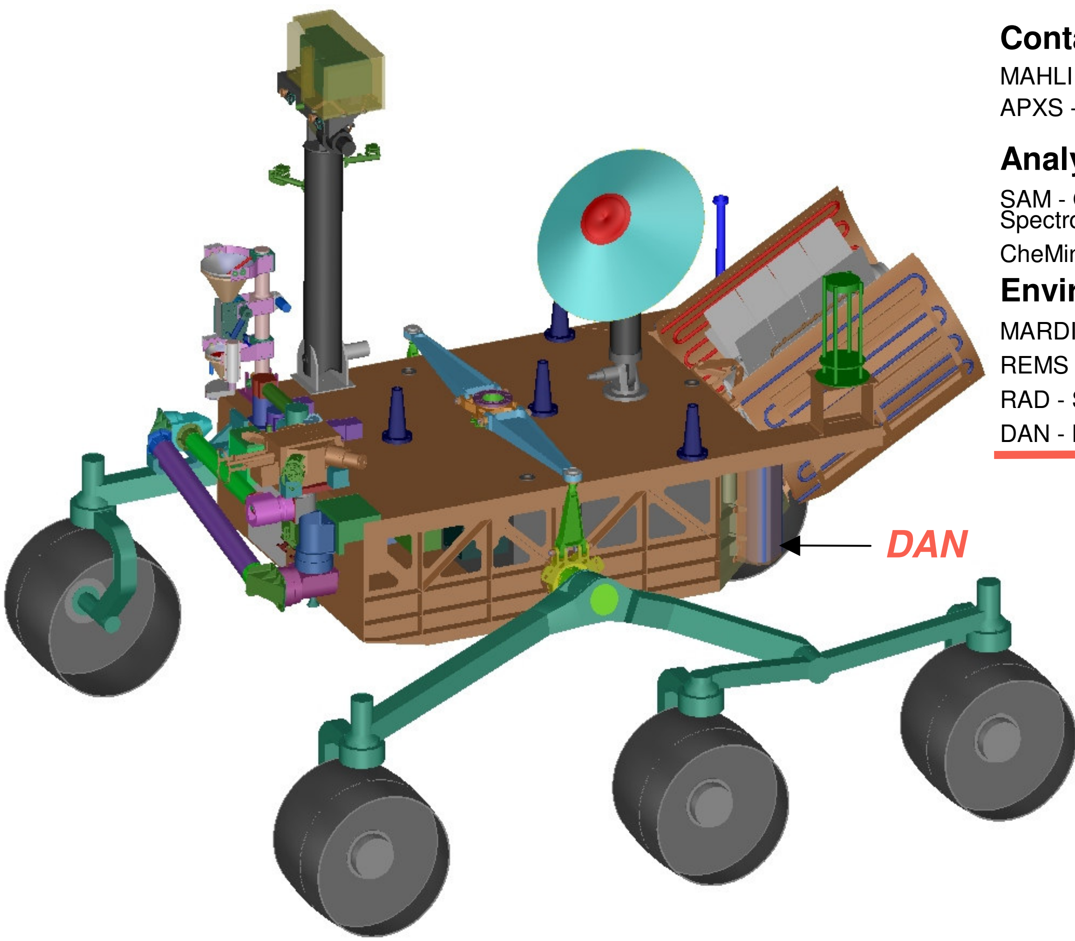






Russian Detector of Albedo Neutrons (DAN) will go to Mars on NASA "Mars Science Laboratory" 2008

Science Instruments of MSL



DAN

Remote Sensing (Mast)

ChemCam – Laser Induced Breakdown Spectrometer
MastCam - Color Stereo Imager

Contact Instruments (Arm)

MAHLI - Microscopic Imager
APXS - Proton/X-ray Backscatter Spectrometer

Analytical Laboratory (Front Chassis)

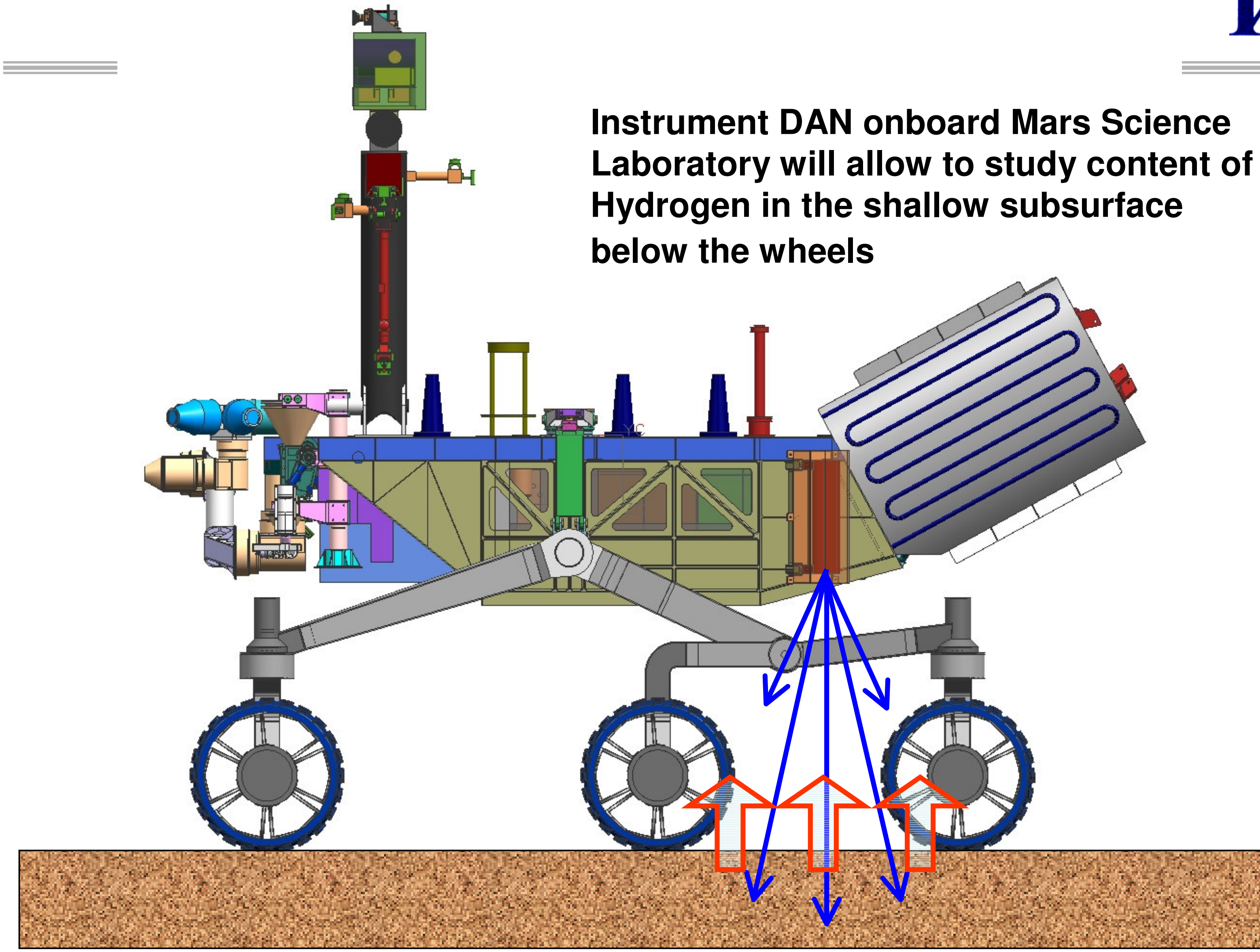
SAM - Gas Chromatograph/Mass Spectrometer/ Tunable Laser Spectrometer (Sample Composition / Organics Detection)
CheMin - X-ray Diffraction / Florescence (Sample Mineralogy)

Environmental Characterization (Body-mount)

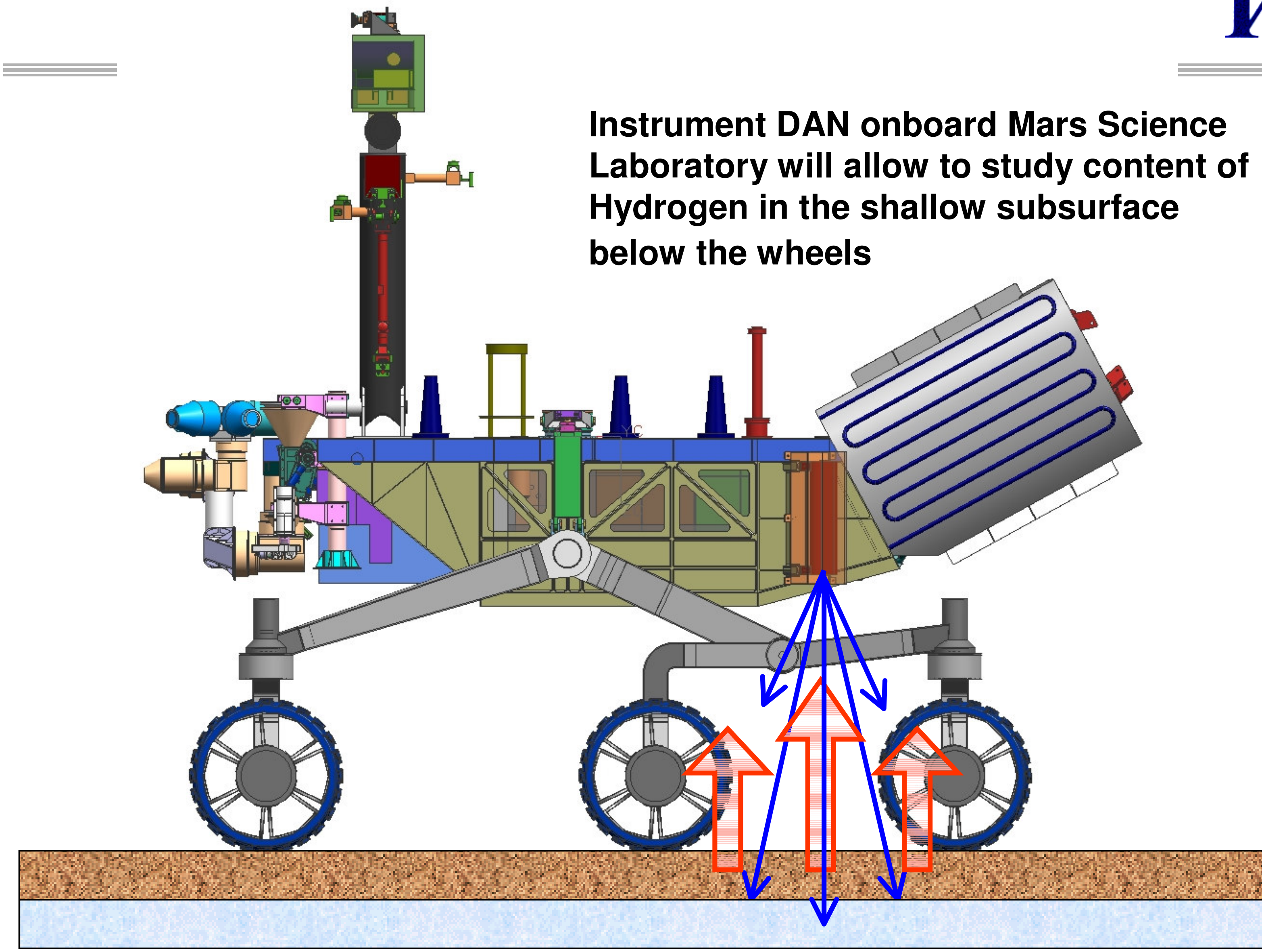
MARDI - Descent Imager
REMS - Meteorological monitoring
RAD - Surface Radiation Flux Monitor (future human health & safety)
DAN - Neutron Backscatter subsurface hydrogen (water/ice) detection

Project Science Group
R. Weins, LANL - ChemCam
M. Malin, MSSS - MastCam, MARD
K. Edgett, MSSS - MAHLI
D. Blake, NASA ARC - CheMin
P. Mahaffy, NASA GSFC - SAM
R. Gelhert, Max Plan IfC - APXS
I. Mitrofanov, IKI - DAN
L. Vasquez, INTA/CABS - REMS
D. Hassler, SwRI - RAD

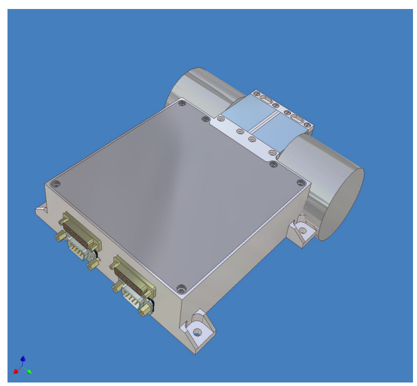
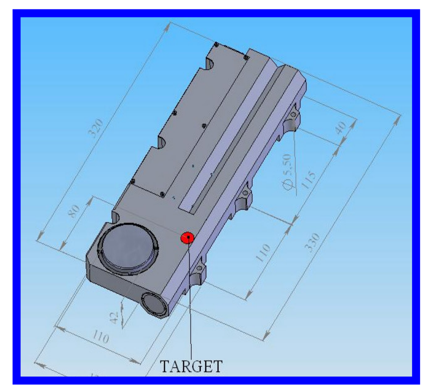
Instrument DAN onboard Mars Science Laboratory will allow to study content of Hydrogen in the shallow subsurface below the wheels



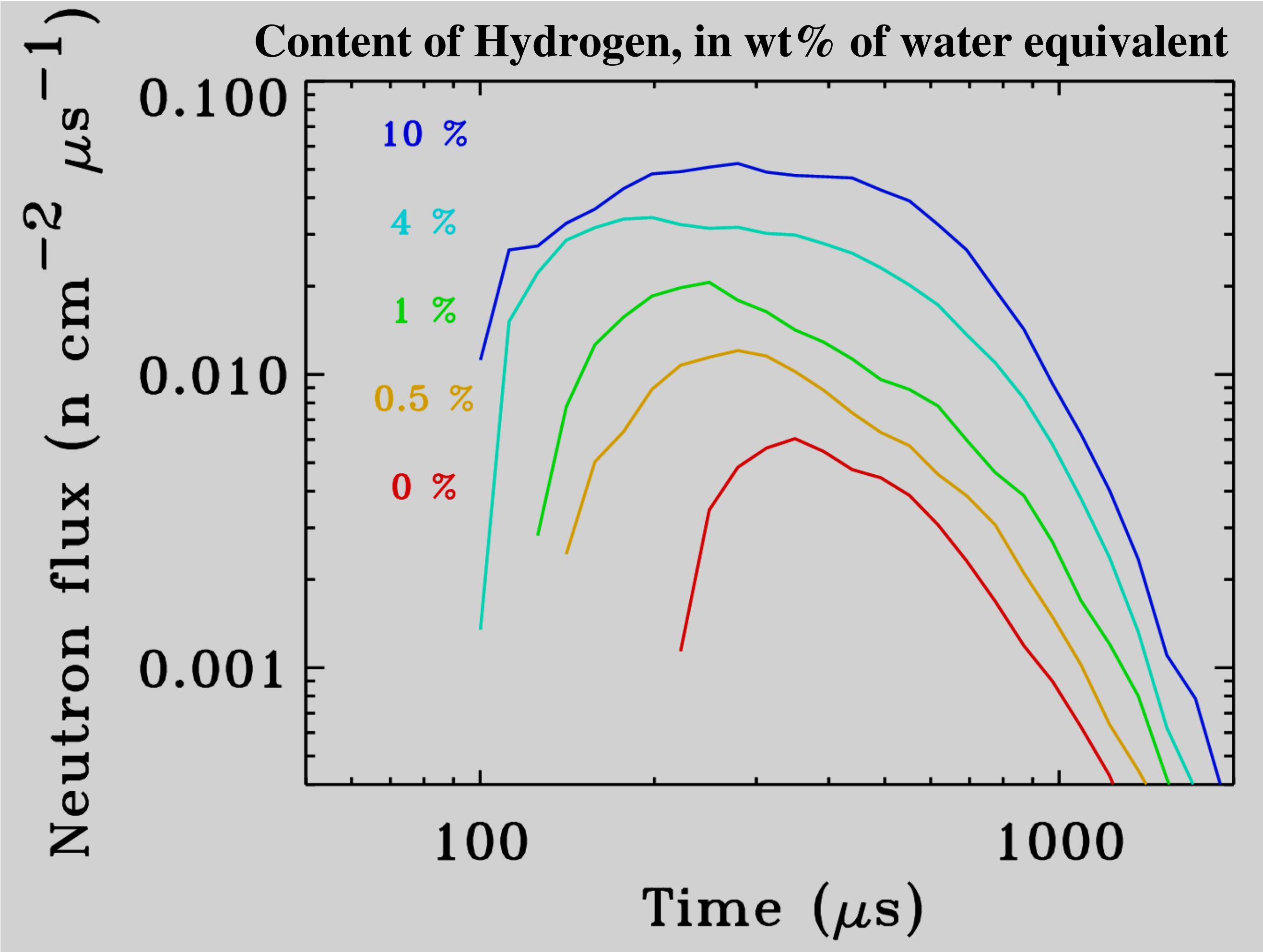
Instrument DAN onboard Mars Science Laboratory will allow to study content of Hydrogen in the shallow subsurface below the wheels

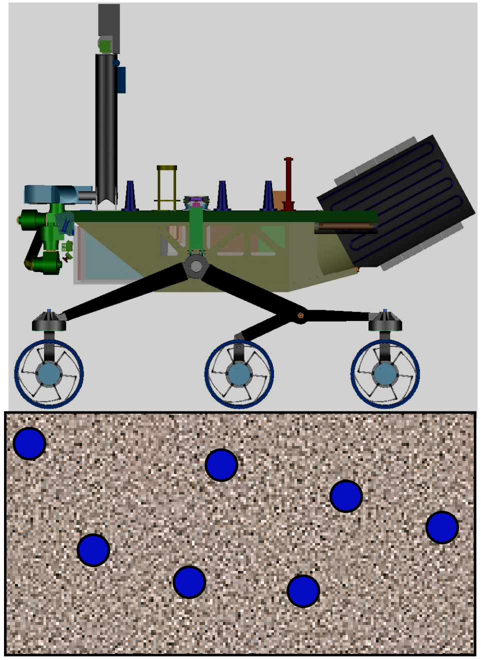


The main DAN characteristics

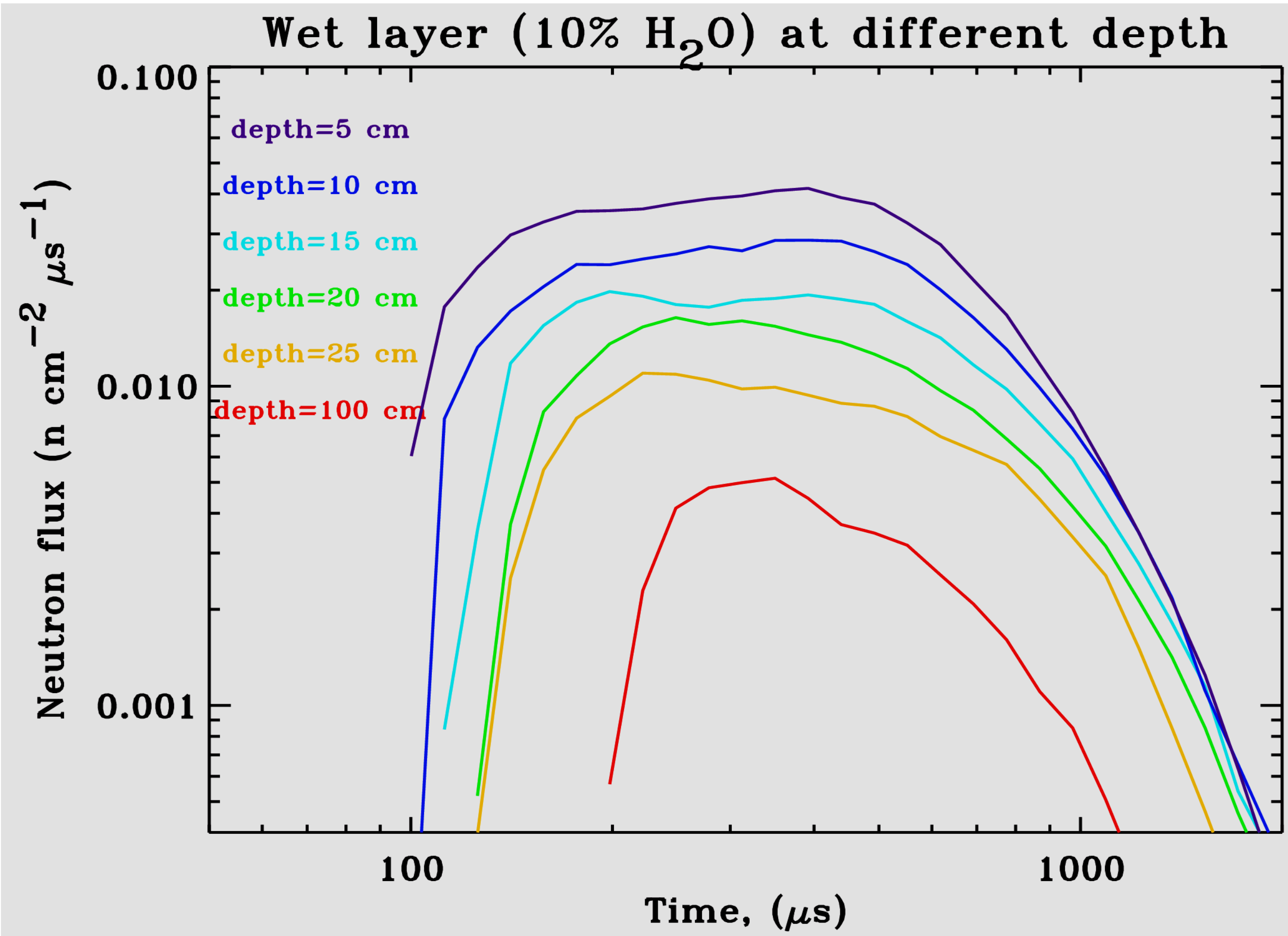
PARAMETER	DAN/DE	DAN/PNG
Mass	1.66 kg + 0.27	2.8 kg + 0.1
Power	3.5 W	11.5 W
Max Dimensions	164 x 205 x 61 mm	120 x 330 x 45 mm
Functions	Neutron detection	Neutron emission
Energy Band	Thermal and epithermal neutrons in wide energy range	Fast neutrons with energy = 14 MeV in pulses 1-2 μs with 10^7 particles
Temporal resolution	1-3 μs	<1 μs
Horizontal resolution	< 1 m	< 1 m
Vertical resolution	1 m	1 m
Life time	5 years	5 years and/or 10^7 neutron pulses
		

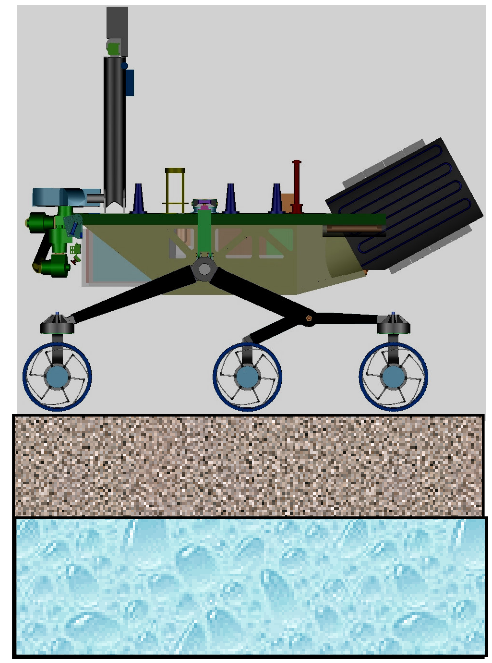
Numerical simulation of die away profile of thermal neutrons albedo: *content of water* in homogeneous "Pathfinder"-like soil



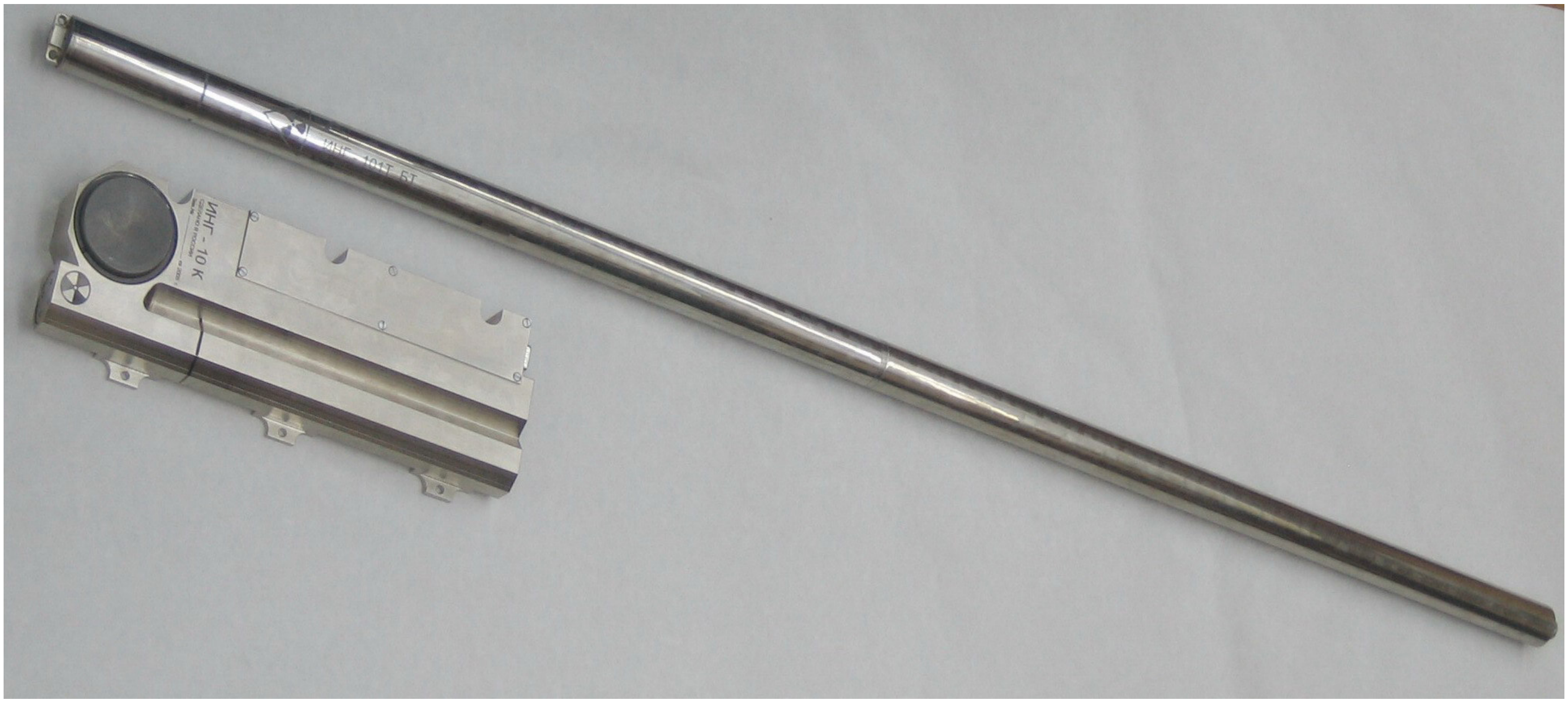


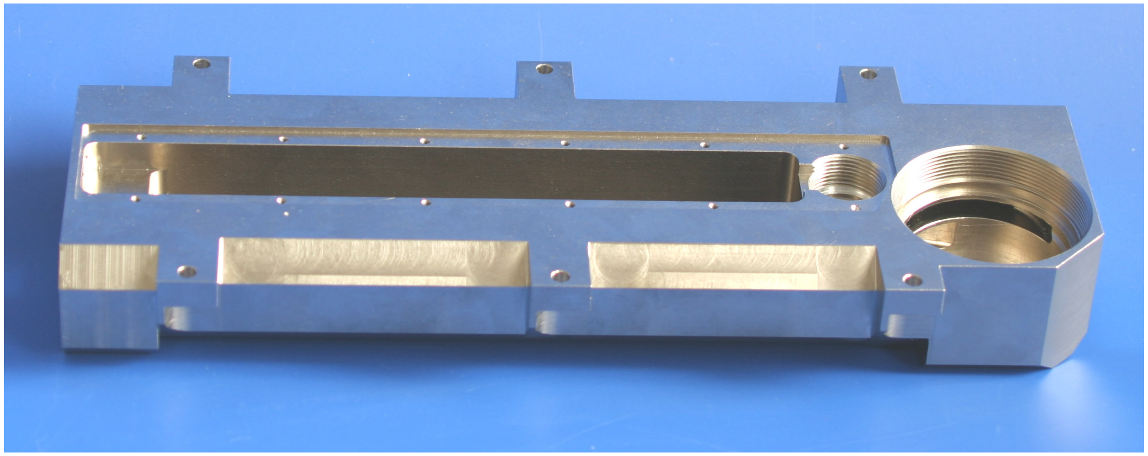
Numerical simulation of die away profile of thermal neutrons albedo: *layering structure of water ice* in "Pathfinder"-like soil





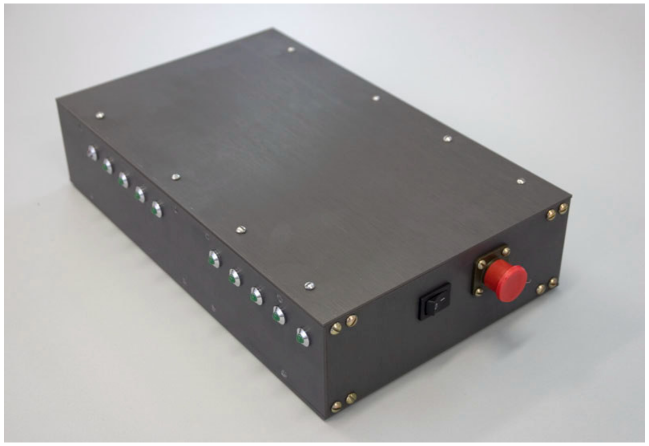
DAN/PNG and its industrial prototype





DAN/PNG main frame

DAN laboratory unit



DAN interface simulator

DAN Science Level 1 Requirements

- **DAN is able to produce at least 10^7 separate microsecond long pulses of with 10^7 neutrons of 14 MeV at each pulse, and to measure thermal and epithermal albedo neutrons with time resolution of 1-3 microseconds**

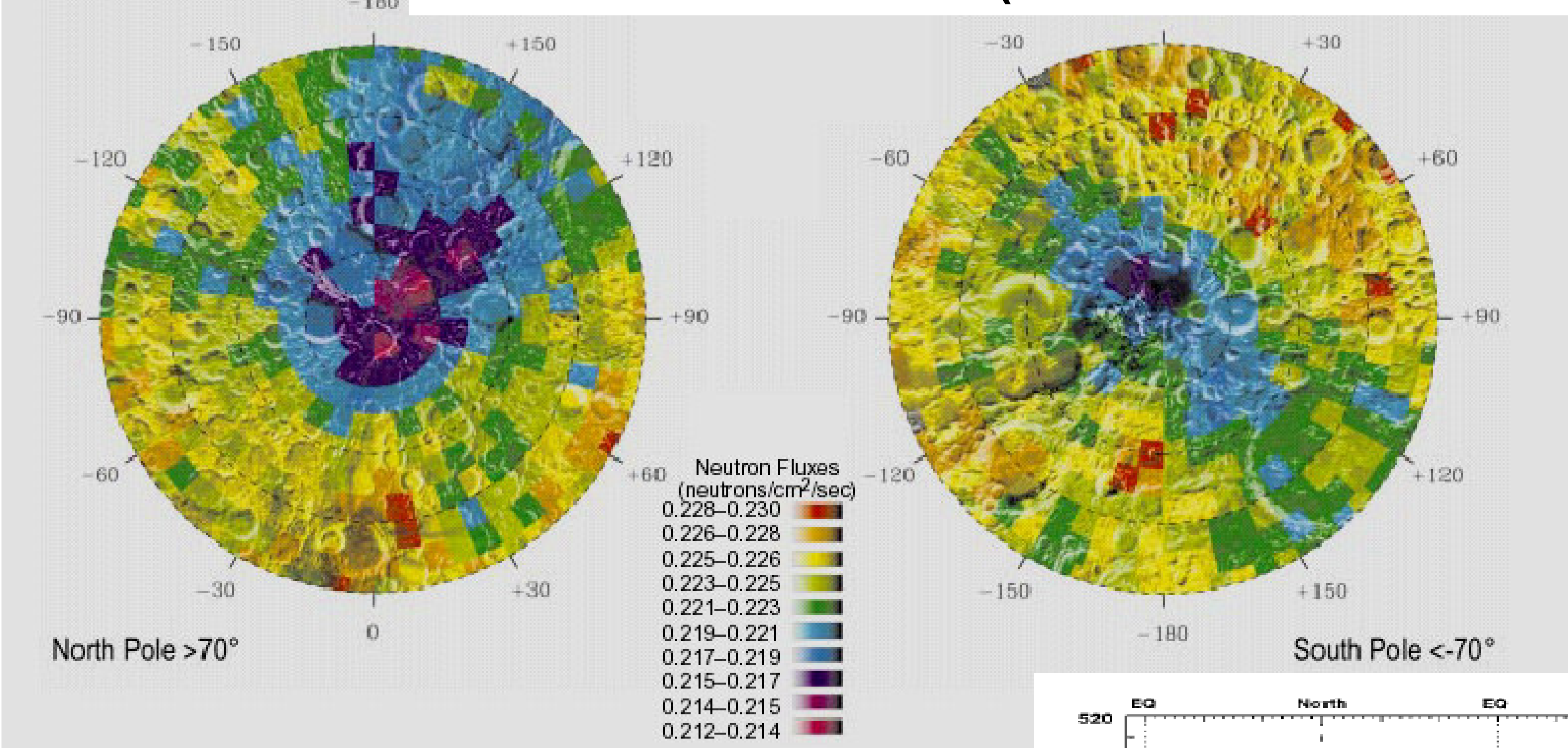
- **There are two types of individual measurement of DAN with 10^2 and $2 \cdot 10^4$ pulses of activation, which corresponds to *monitoring measurement* with accuracy of hydrogen content determination of about 1.0 wt% (water equivalent) and to *water content analysis* with accuracy of hydrogen determination of about 0.1 wt% (water equivalent), respectively.**

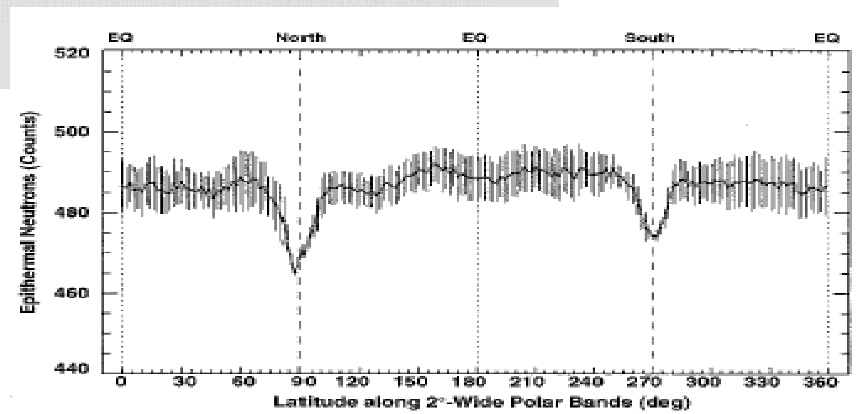
- ***DAN* may produce either at least 10^5 *monitoring measurements* of water content, or at least 500 measurements of *water content analysis*.**

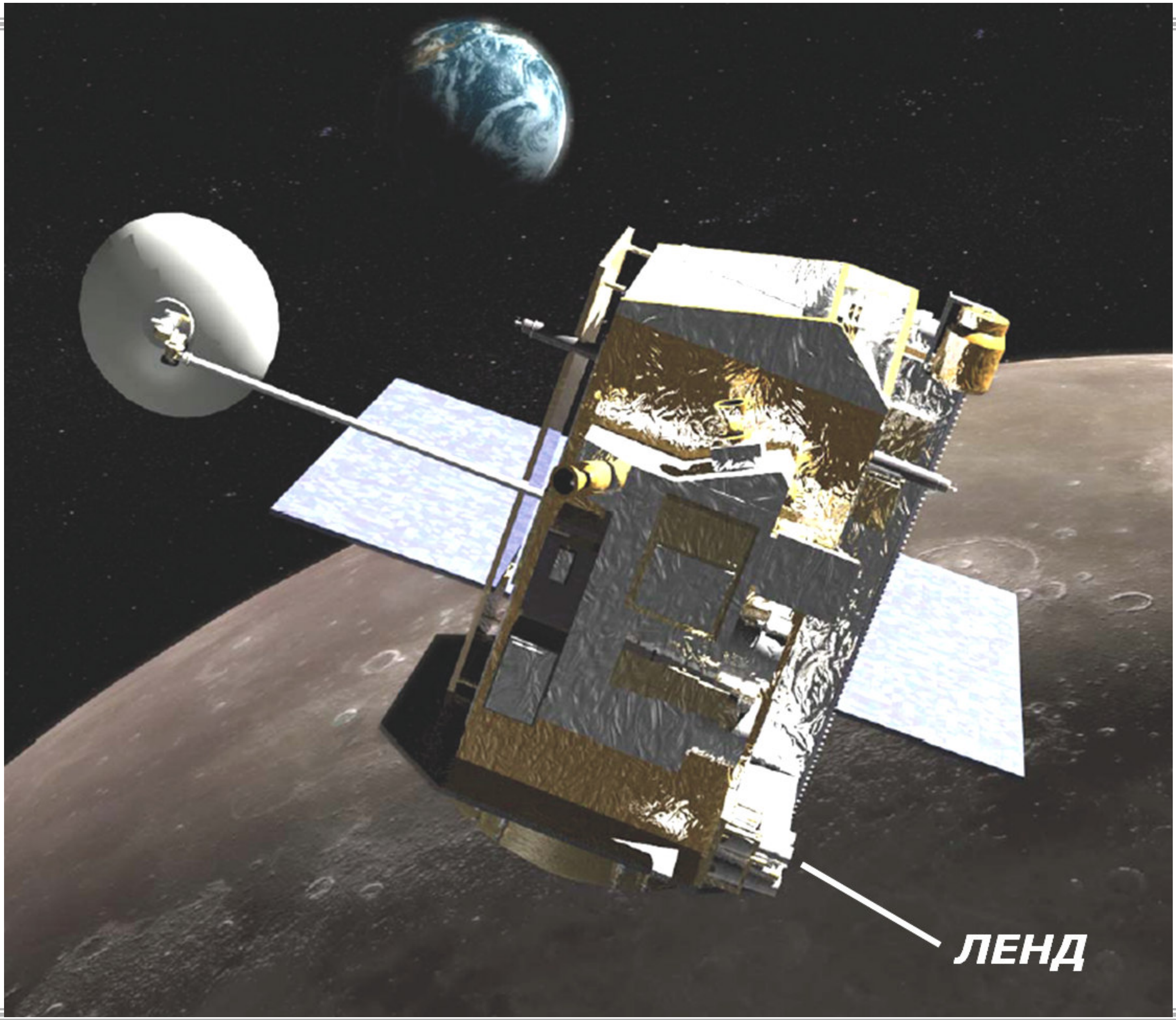
- **Horizontal resolution for the unmoving vehicle corresponds to the size of activated spot about 1 meter. For MSL velocity of 5 cm/s the horizontal scale corresponds to 100 m and to 50 cm for an individual measurement of H content for *water content analysis* or for *monitoring,* respectively, provided PNG produces pulses with the frequency of 10 Hz.**

Russian Lunar Exploration Neutron Detector (LEND) will go the Moon on NASA "Lunar Reconnaissance Orbiter" 2009

…water on the Moon? (neutrons from Lunar Prospector)



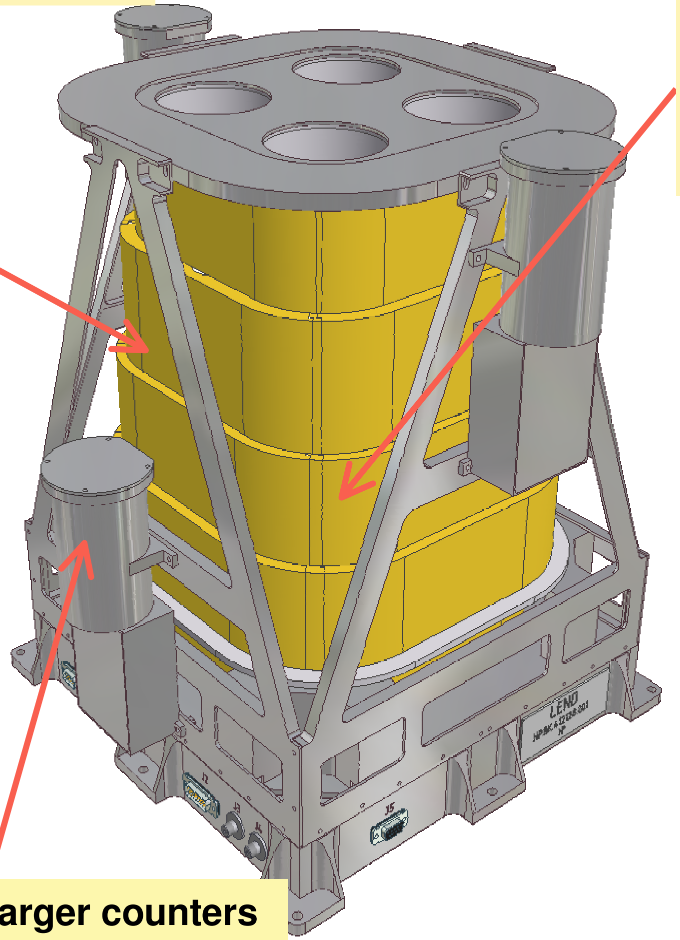



ЛЕНД

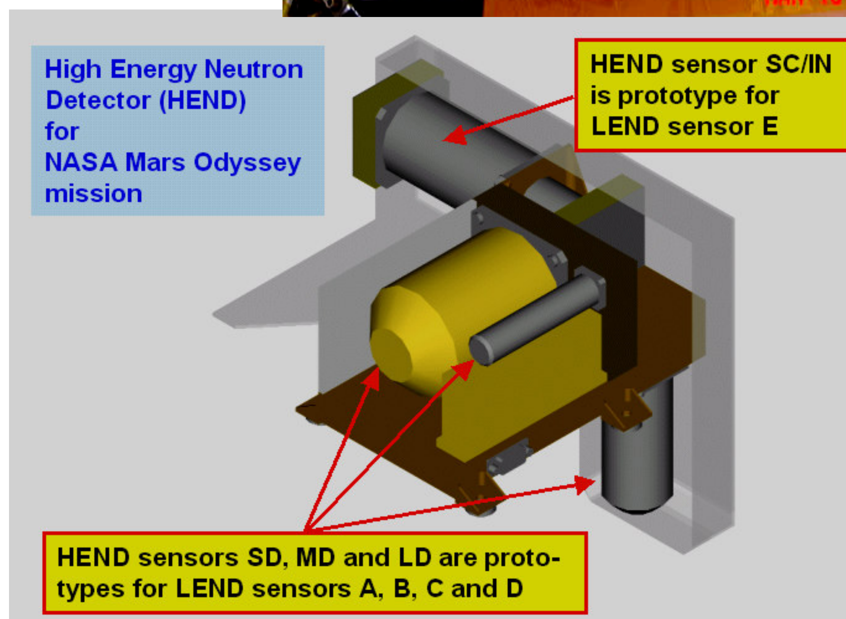
LEND is based on HEND heritage

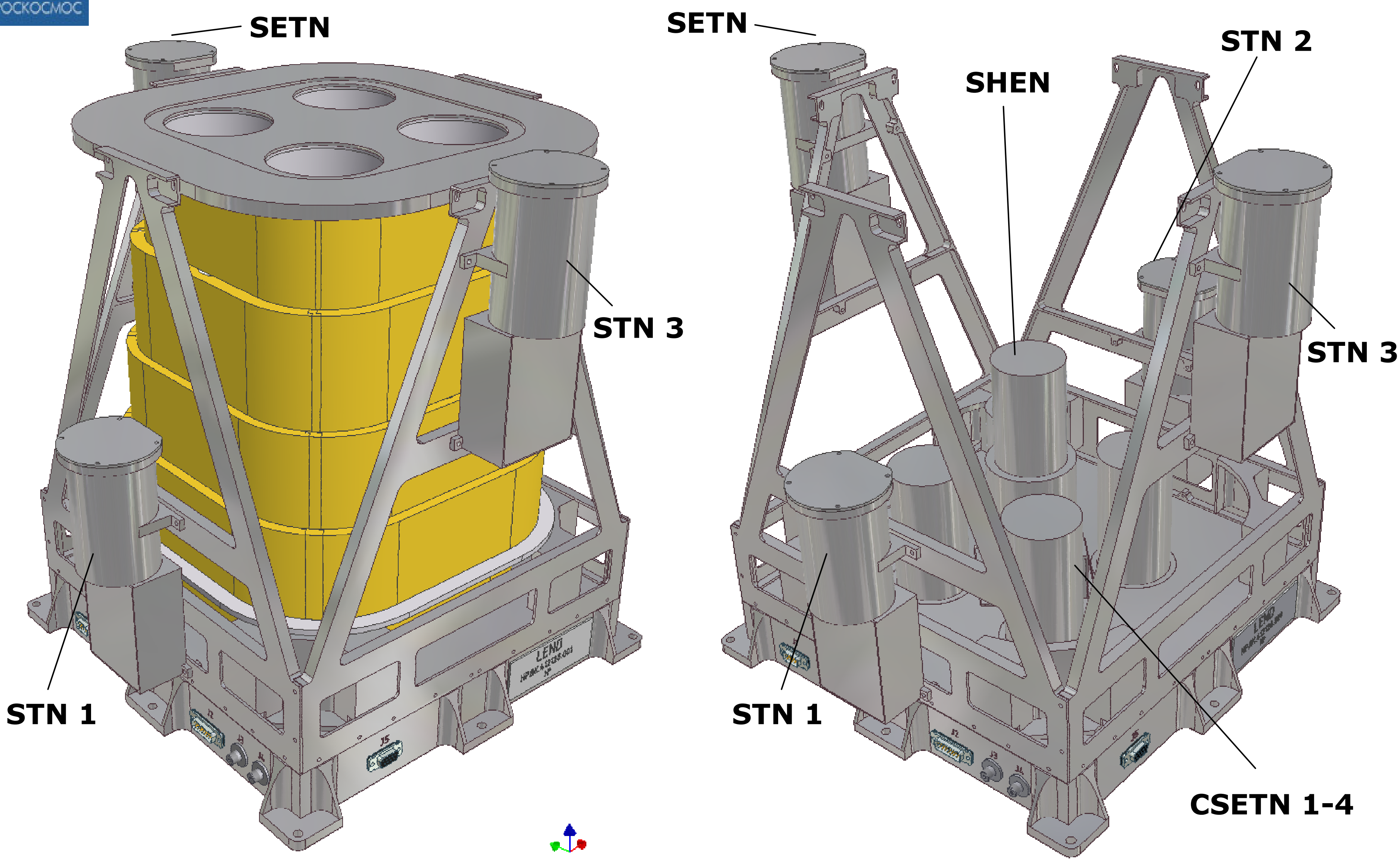
New:
Collimator
of neutrons

New: Plastic
anticoincidence
for sensor
of SHEN



New: Larger counters
of neutrons




SETN
STN 3
STN 1
SETN
STN 2
SHEN
STN 3
STN 1
CSETN 1-4

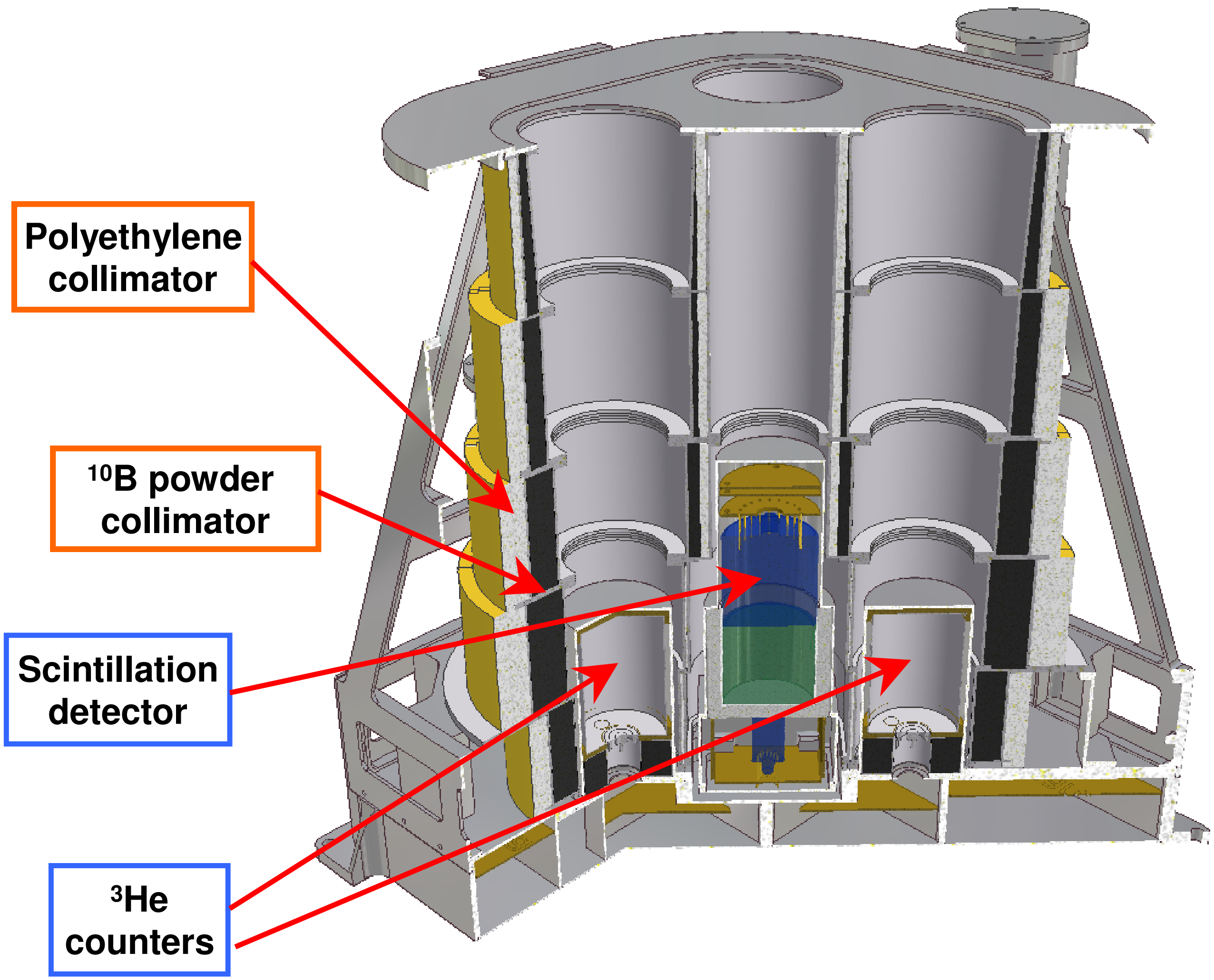
LEND will be the first collimated neutron telescope in space

Total mass of the instrument without MLI:

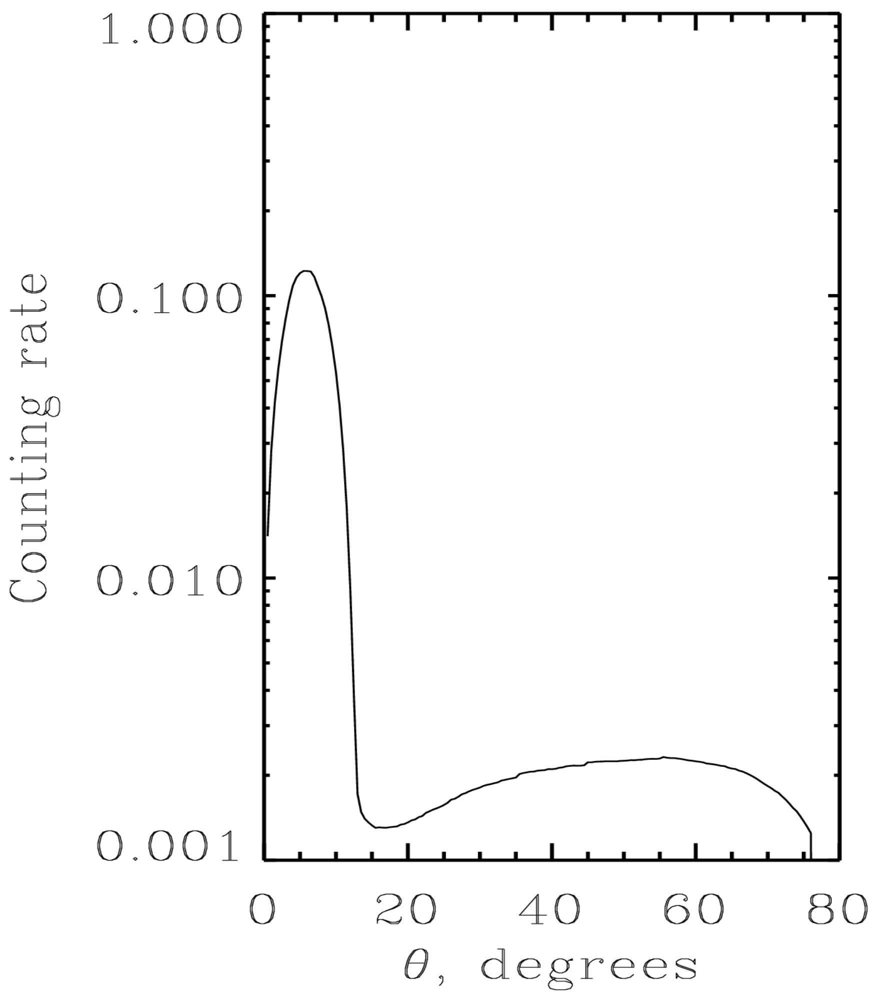
~ 23.2 kg

Total mass of the collimator materials:

~ 15.8 kg



LEND sensitivity was estimated by numerical modeling

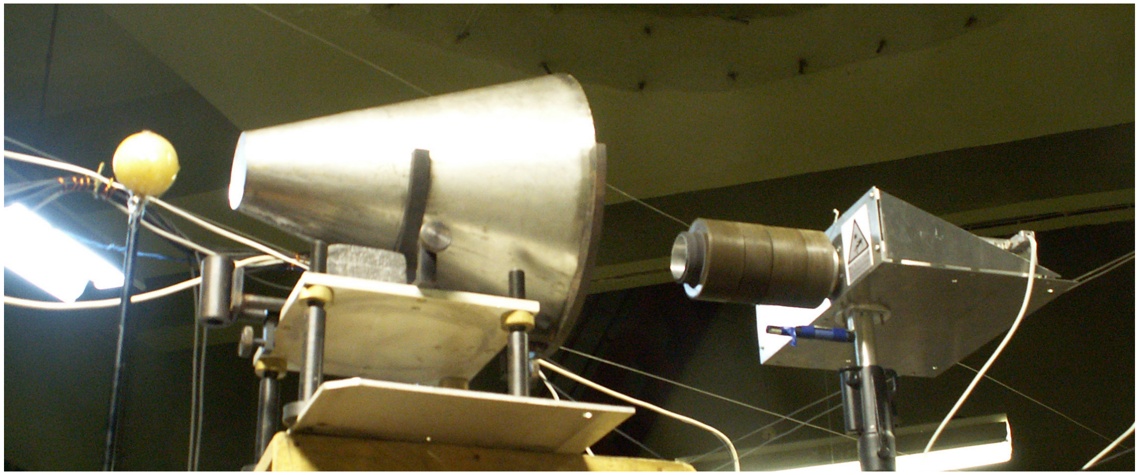


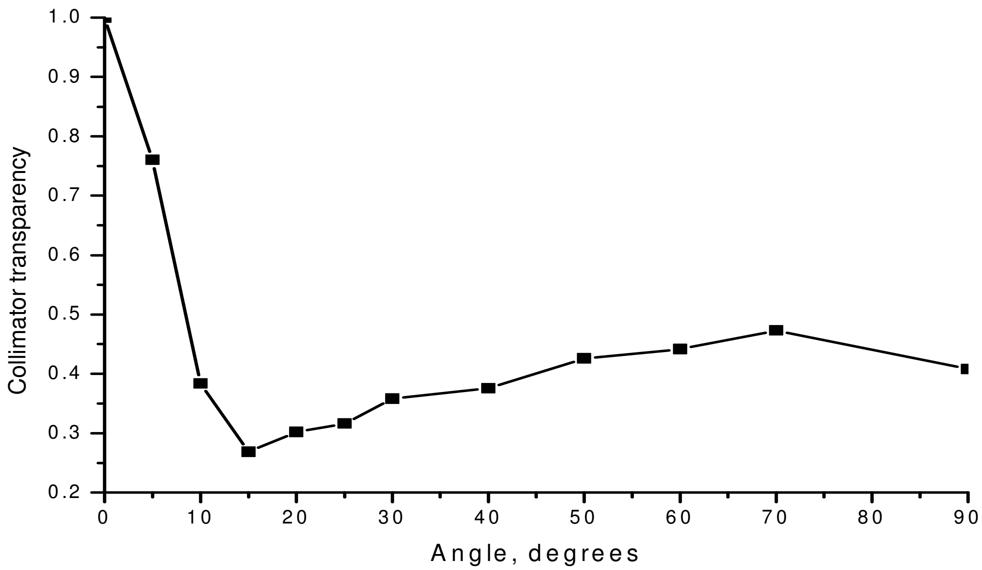
Total counting rate:	**2.1 count/sec**
Field of view:	**5.7°**
N_{FOV}:	**0.9 count/sec**
N_{bgd}:	**1.2 count/sec**
N_{bgd} / N_{FOV}:	**1.3**

The modeled instrument sensitivity to hydrogen in a polar spot with 10 km diameter is

70 ppm

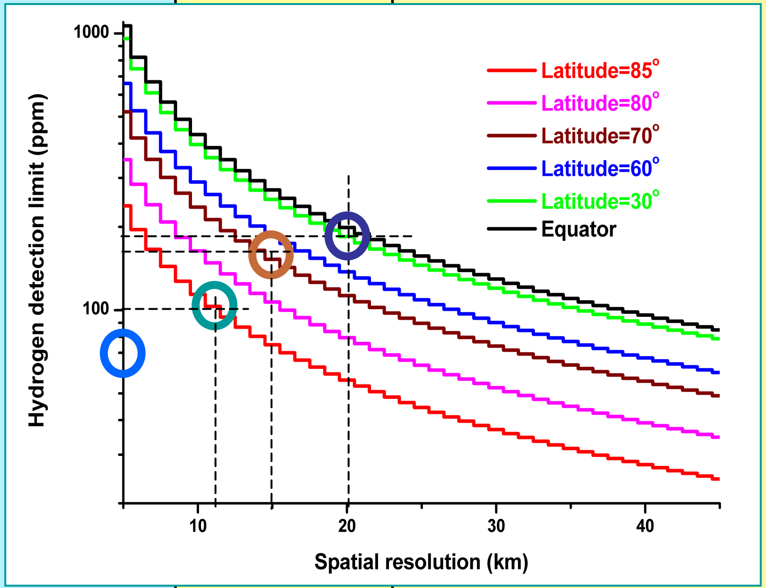
LEND sensitivity was tested with laboratory prototype





LEND Data Products for LPRP

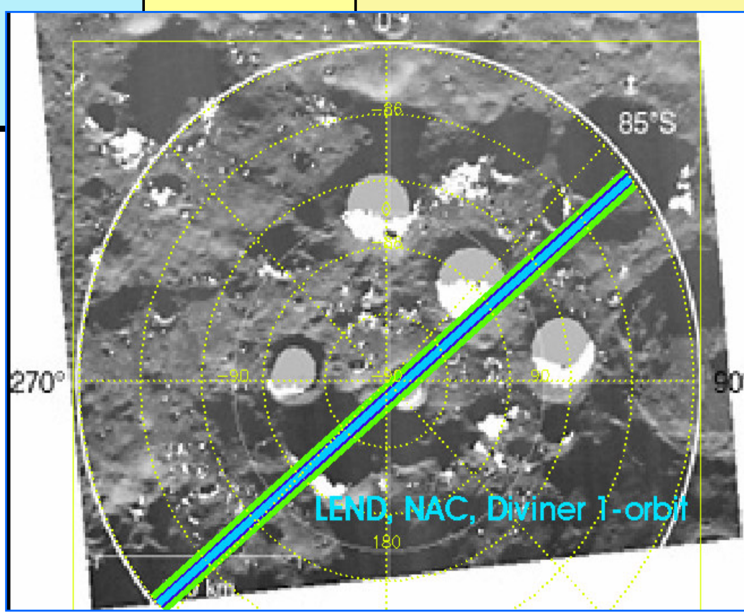
LRO Req.	Level 1: Requirements		
	Instrument	LRO Mission Requirement	Required Data Products (LEND Level 3)
RLEP-LRO-M110	LEND IMR 1: Hydrogen mapping	The LRO shall obtain high spatial resolution hydrogen mapping of the Moon's surface to a 20% accuracy and 5 km resolution at the poles.	PDR: Determine hydrogen content of subsurface at polar regions with spatial resolution from Half-Width Half-Maximum (HWHM)=5km and with variation sensitivity from 100 parts per million (ppm) CDR: ***Surface Composition Data Product (I)***:



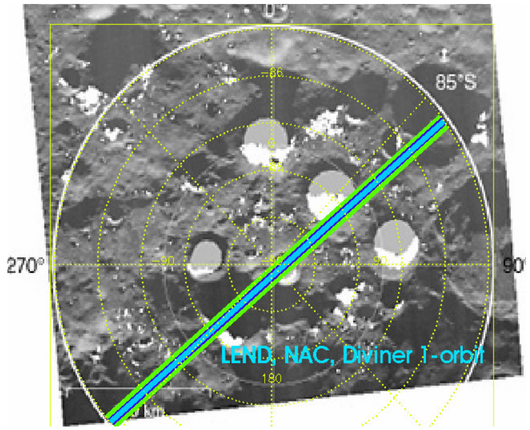
Regions	Spatial resolution (km)	Detection limit (ppm 3 sigma)
Poles	5.0	70
85 LAT	12.0	100
70 LAT	15.0	150
30 LAT	20.0	180
Equator	30.0	200

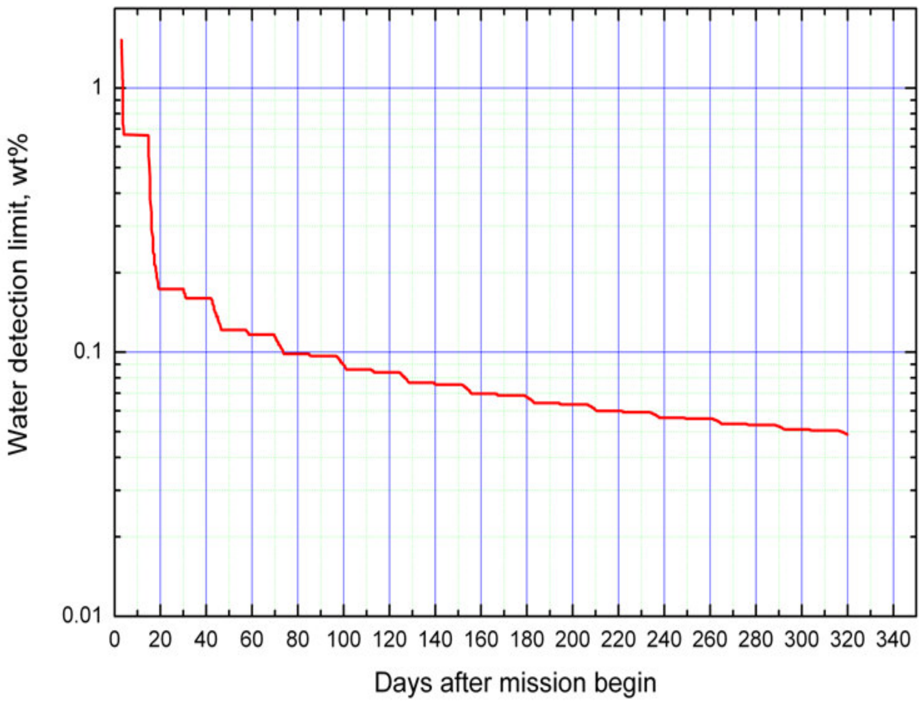
LEND Data Products for LPRP

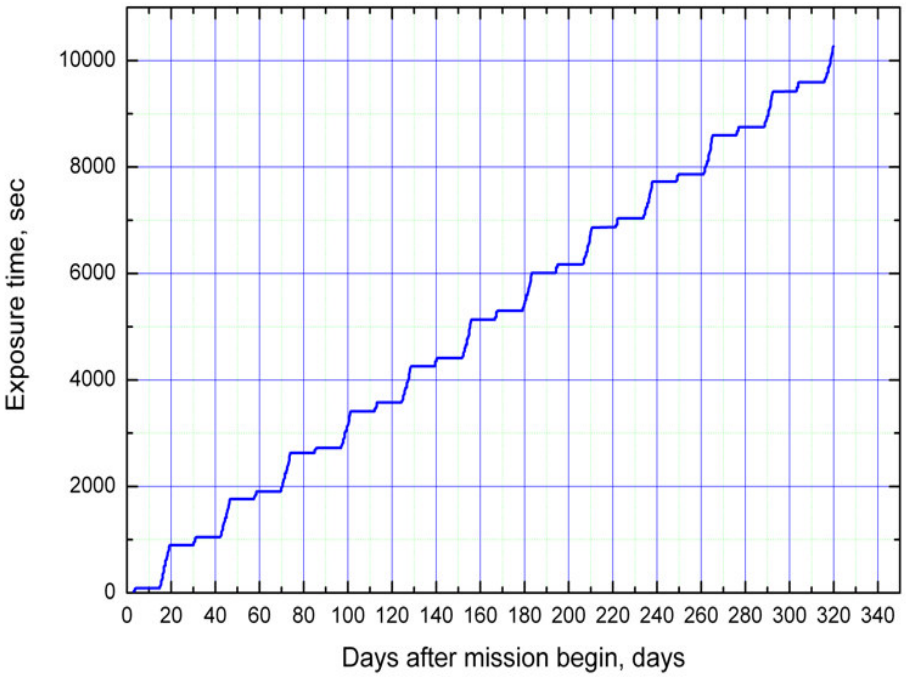
LRO Req.	Level 1: Requirements		
	Instrument	LRO Mission Requirement	Required Data Products (LEND Level 3)
RLEP-LRO-M070	LEND IMR 2: Testing for water ice	The LRO shall identify putative deposits of appreciable surface or near surface water ice in the Moon's polar cold traps at 100m scale spatial resolution	PDR: Develop maps of water ice column density on polar regions of the Moon with spatial resolution from 5-20km. CDR: ***<u>Surface Composition Data Product (II):</u>*** - Estimation of column density of water ice for particular targets (permanently shadowed craters)



LEND will be able to "image" potential targets for LCROSS at the very beginning of the mission: example of Shoemaker

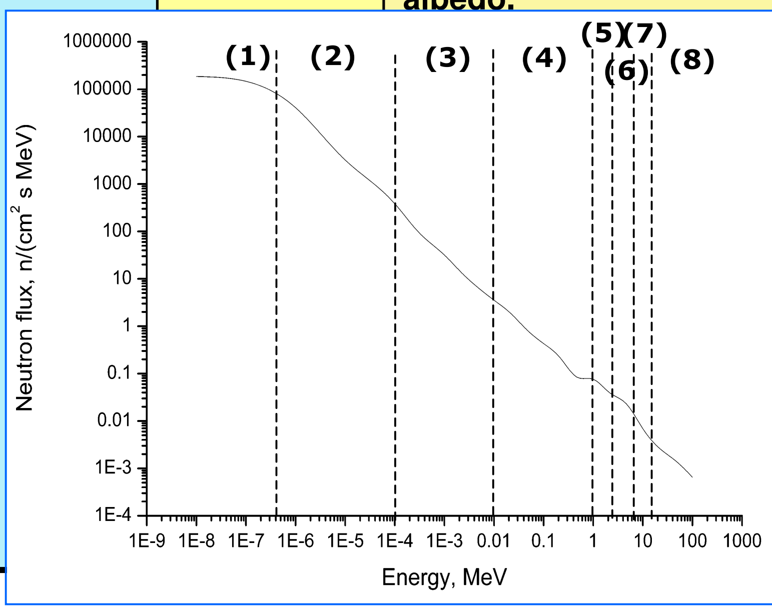






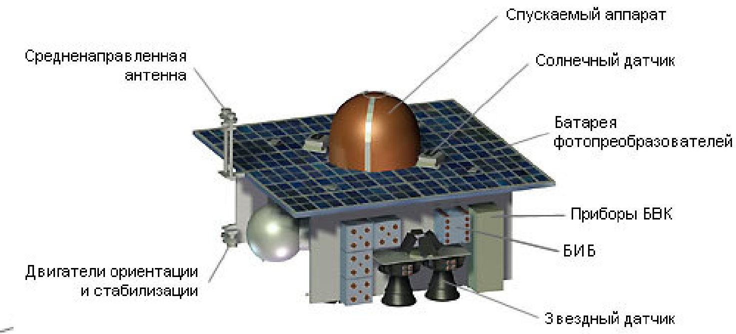
LEND Data Products for LPRP

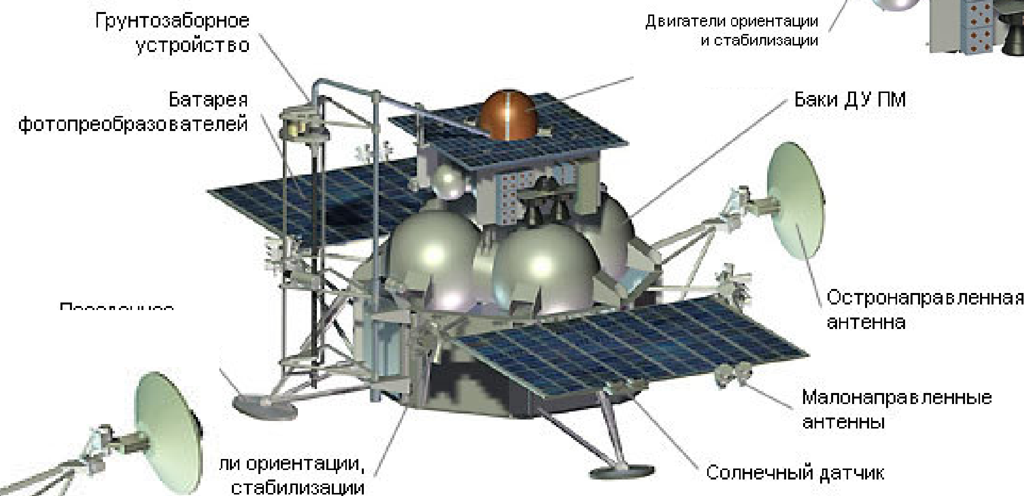
LRO Req.	Level 1: Requirements		
	Instrument	LRO Mission Requirement	Required Data Products (LEND Level 3)
RLEP-LRO-M010	LEND IMR 3 Radiation environmen	The LRO shall characterize the deep space radiation environment in lunar orbit, including neutron albedo.	PDR:Radiation Data Product for global distribution of neutrons at Moon's orbit with spatial resolution of 50 km at different energy ranges from thermal energy up to >15 MeV separately for periods of quiet Sun and for periods of Solar Particle Events. CDR: *__Radiation Data Product__*: GLOBAL MAPPS of NEUTRON FLUX at EGHT ENERGY RANGES WITH SPATIAL RESOLUTION 5-30 km (1) < 0.4 eV, (2) 0.4 – 100 eV, (3) 0.1 keV – 10 keV; (4) 10 keV – 1.0 MeV; (5) 1.0 –2.5 MeV, (6) 2.5 – 7.5 MeV (7) 7.5 - 15.0 MeV and (8) > 15.0 MeV

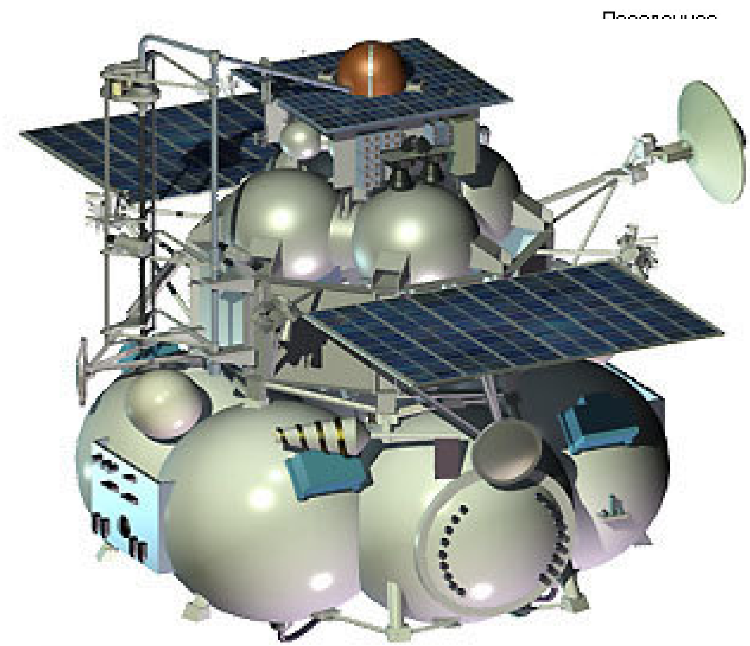


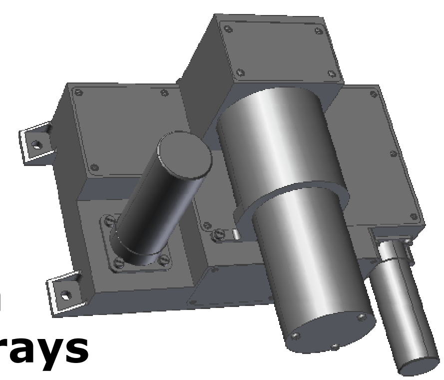
Future perspectives of cooperation

Russian mission PHOBOS-GRUNT 2009 for Phobos soil return



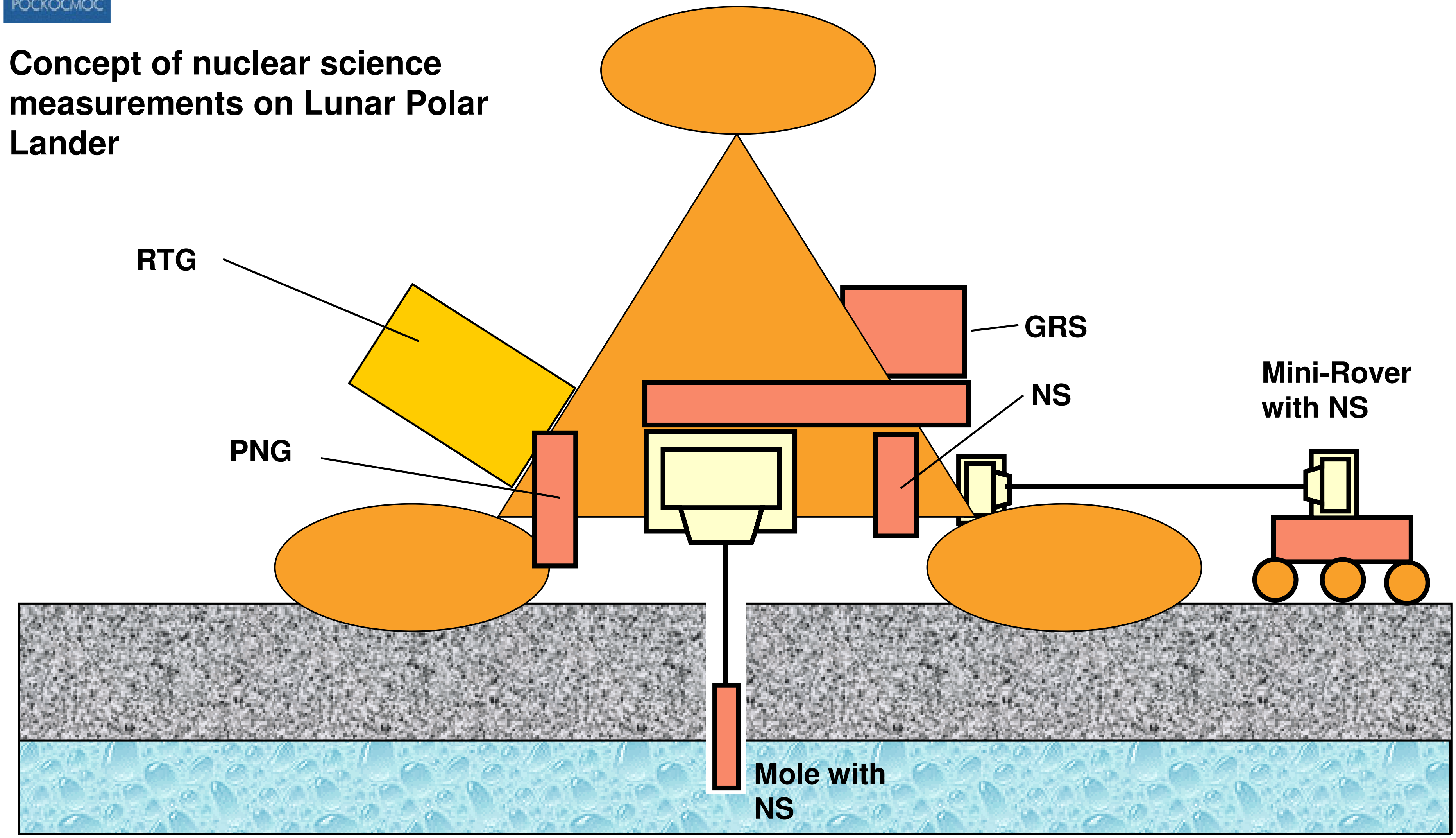






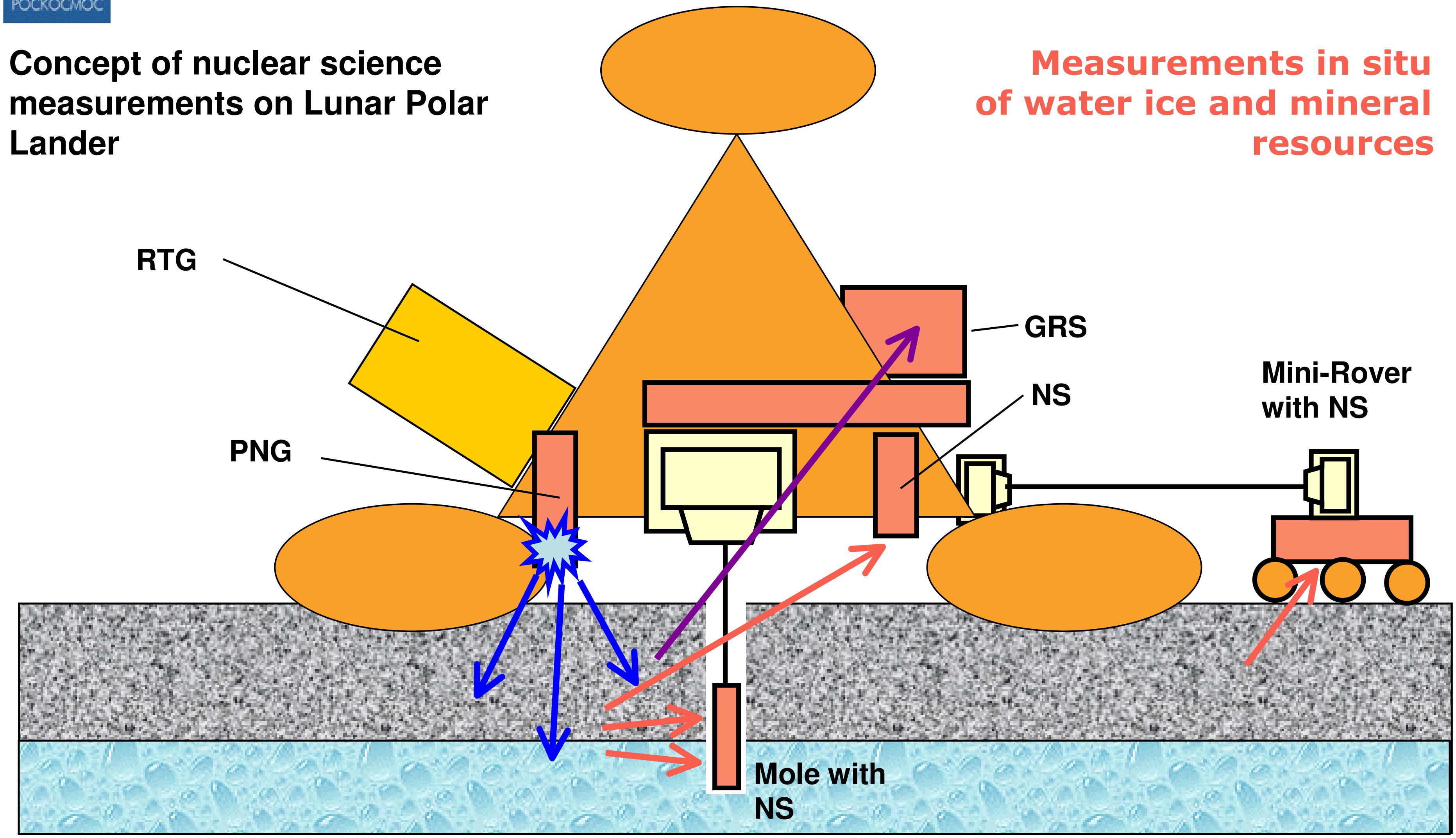
Instrument HEND-Phobos for in situ characterization of Phobos soil by gamma-rays and neutrons

Concept of nuclear science measurements on Lunar Polar Lander



Concept of nuclear science measurements on Lunar Polar Lander

Measurements in situ of water ice and mineral resources



Concept of nuclear science measurements on Lunar Polar Lander

Measurements in situ of water ice and mineral resources